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

Decision letter and referee reports: first round

19th May 20

Dear Dr. Skinner,

Please allow me to apologise for the delay in reaching a decision on your manuscript titled "Southern Ocean convection amplified past Antarctic warming and CO₂rise". It has now been seen by 3 reviewers, and I include their comments at the end of this message. They find your work of interest, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication.

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

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

Please use the following link to submit your revised manuscript, point-by-point response to the referees’ comments (which should be in a separate document to any cover letter) and the completed checklist:
[link redacted]
** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

We hope to receive your revised paper within four weeks; please let us know if you aren’t able to submit it within this time so that we can discuss how best to proceed. If we don’t hear from you, and the revision process takes significantly longer, we may close your file. In this event, we will still be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

We understand that due to the current global situation, the time required for revision may be longer than usual. We would appreciate it if you could keep us informed about an estimated timescale for resubmission, to facilitate our planning. Of course, if you are unable to estimate, we are happy to accommodate necessary extensions nevertheless.

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

Best regards,

Joe Aslin

Associate Editor,

Communications Earth & Environment
https://www.nature.com/commsenv/
Twitter: @CommsEarth

EDITORIAL POLICIES AND FORMATTING

We ask that you ensure your manuscript complies with our editorial policies. Please ensure that the following formatting requirements are met, and any checklist relevant to your research is completed and uploaded as a Related Manuscript file type with the revised article.

Editorial Policy: Policy requirements

Furthermore, please align your manuscript with our format requirements, which are summarized on the following checklist:
Communications Earth & Environment formatting checklist

In the event that the manuscript is accepted we will be providing further guidance on formatting but please ensure that the manuscript generally complies with our house style at this stage. The main points are as follows:

* ABSTRACT: less than 150 words and accessible. It should include the background and context of the work, the phrase 'Here we' (present/show/suggest) to indicate where the description of your own work starts, and then the methods/data, main results and conclusions of the paper.

*The text must be split into:
- INTRODUCTION (<1000 words): includes the background and rationale for the work. The final paragraph should be a brief summary of the main results and conclusions. The results of the current study should only be discussed in this final paragraph.
- RESULTS: split into subheaded sections; ensure that the subheadings are no longer than 60 characters including spaces.
- DISCUSSION: without subheadings.
- METHODS: split into subheaded sections; ensure that the subheadings are no longer than 60 characters including spaces

* SUPPLEMENTARY INFORMATION should be organised logically, with all items labelled as one of the following item types, and cited in the main article:
- Supplementary Figures, labelled and referred to as i.e. Supplementary Figure 1 throughout both the Supplementary Information and the main text
- Supplementary Tables, labelled as above
- Supplementary Notes, labelled as above
- Supplementary Discussion
- Supplementary Methods
- Supplementary References

Data: All Communications Earth & Environment manuscripts must include a section titled "Data Availability" at the end of the Methods section or main text (if no Methods). More information on this policy, and a list of examples, is available at http://www.nature.com/authors/policies/data/data-availability-statements-data-citations.pdf.
In addition, Communications Earth & Environment endorses the principles of the Enabling FAIR

data project (http://www.copdess.org/enabling-fair-data-project/). We ask authors to make the data that support their conclusions available in permanent, publically accessible data repositories. (Please contact the editor if you are unable to make your data available).
In particular, the Data availability statement should include:
- Unique identifiers (such as DOIs and hyperlinks for datasets in public repositories)
- Accession codes where appropriate
- If applicable, a statement regarding data available with restrictions
- If a dataset has a Digital Object Identifier (DOI) as its unique identifier, we strongly encourage including this in the Reference list and citing the dataset in the Data Availability Statement.

DATA SOURCES: All new data associated with the paper should be placed in a persistent repository where they can be freely and enduringly accessed. We recommend submitting the data to discipline-specific, community-recognized repositories, where possible and a list of recommended repositories is provided at http://www.nature.com/sdata/policies/repositories.

If a community resource is unavailable, data can be submitted to generalist repositories such as figshare or Dryad Digital Repository. Please provide a unique identifier for the data (for example a DOI or a permanent URL) in the data availability statement, if possible. If the repository does not provide identifiers, we encourage authors to supply the search terms that will return the data. For data that have been obtained from publically available sources, please provide a URL and the specific data product name in the data availability statement. Data with a DOI should be further cited in the methods reference section.

Please refer to our data policies at http://www.nature.com/authors/policies/availability.html.

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

See PDF attached.

Reviewer #2 (Remarks to the Author):

Review of "Southern Ocean convection amplified past Antarctic warming and CO2 rise", by L. Skinner, L. Menviel, L. Broadfield, J. Gottschalk and M. Greaves

Significance: The complicated, although at times anti-phased, responses of the northern and southern hemispheres during the last glacial period have often been described as a "bi-polar seesaw". The cognitive appeal of this metaphor – which is directly related to the cognitive appeal of the "global conveyor belt" metaphor – has been hard to overcome, despite the significant evidence that most of the details implied by the see-saw metaphor (heat sloshes back and forth between the poles through the ocean) are just unfounded or contrary to the paleo evidence. This study of Heinrich Stadial 4 (~38-40 kya), which combines details from benthic foraminifera associated with deep ocean temperatures, oxygenation levels and radio-carbon ages from the deep Atlantic with model simulations, adds to the significant body of evidence that changes in the Southern Ocean circulation (not caused or driven by the AMOC) are largely responsible for the observed ventilation and carbon and heat storage changes that drove the atmospheric changes in carbon and heat.

Summary: This study analyzes benthic foraminifera from the South Atlantic during the period that covers Heinrich Stadial 4 (HS4, ~38-40kya) and compares the reconstructed temperature and oxygenation time series to concurrent atmospheric and oceanographic time series from the northern and southern hemispheres. They compare these data to numerical simulations in which changes are forced from each hemisphere – either increased southern ocean convection or decreased Atlantic meridional overturning – and find that the data are most consistent with increased Southern Ocean deep convection. They conclude that the warming in Antarctic temperature coincident with the stadial event (cooling) in the north had nothing to do with a purported "bi-polar seesaw" mechanism, but was driven by the release of stored heat due to increased deep convection. They also suggest that mid-depth ventilation (again from the south) might also be important to the observed Antarctic temperature pattern.

Assessment: This a careful and thorough study. In general, fully-coupled simulations are best for assessing the global climate because only coupled simulations include the significant feedbacks between the ocean and the strength and position of the surface winds, but the intermediate-complexity models they use, while not ideal, are good enough to assess the broad impacts of the imposed climate forcing. I'm delighted to see another paper with specific evidence debunking the "bipolar seesaw" and the AMOC mechanism and metaphor.

Recommendation: Accept and publish.

Reviewer #3 (Remarks to the Author):

The manuscript provides a very interesting new record of deep-water temperature estimates across the Heinrich Stadial 4 based on Mg/Ca ratios of two different species of benthic foraminifera in the Atlantic sector of the Southern Ocean. In combination with previously published proxy records for deep ocean ventilation changes, the authors claim to have now strong evidence for a significant increase in Southern Ocean deep convection, starting with a reduction in AMOC circulation associated with the Heinrich Stadial 4. The authors further infer that this increased Southern Ocean convection during cold climate stadials was probably accompanied by an increase in heat and carbon dioxide release to the atmosphere, that could explain to a certain degree the full amplitude of atmospheric warming and CO_2 increase as recorded in Antarctic ice core records for periods of Northern Hemisphere cooling and AMOC reduction at millennial timescales. The authors seek to support this hypothesis by experiments with two coupled atmosphere-ocean circulation models, artificially forcing deep convection in the Southern Ocean parallel to diminishing Northern Hemisphere overturning by freshwater input. In conclusion, the important novelty in this contribution is the evidence stemming from the marine proxy records that support a substantial role in SO heat and gas exchange between the ocean interior and the atmosphere to explain the ´bipolar seesaw hypothesis´ As this is in contrast to other scenarios assuming a redistribution of heat between hemispheres mainly by surface circulation changes, this alternative explanation in turn has also important implications for the development of robust future climate change scenarios. Therefore, I consider the manuscript an important new contribution to the wider community worth the publication.
However, prior to publication the manuscript should be carefully revised and a few arguments re-considered or specified more clearly.
1) Introduction: Lines 50 to 58 address the time lag of a few centuries between NH cooling and the Antarctic response across climate interstadials. This is not taken up later in the discussion whether the alternative explanation in terms of thermal and gas exchange response from the deeper Southern Ocean is also in favor for such a delay. Therefore I recommend to either skip this item here in the introduction or address it later in the discussion again, for example, as an explanation

why the deep ocean cooling does not cease immediately with the end of HS4.

2) Methods and Results: In the supplementary information, the authors add to the existing ´calibration´ data sets new core-top data for Uvigerina sp (Table S1). However, in Fig S1 the value for the Mg/Ca ratio at the lowest temperature 0.99 °C is lacking, why? In addition, the authors should clearly point to the fact, that the temperature range reconstructed for the time interval of interest is not covered by the temperature range of calibration, particularly not for the negative values. Furthermore, it is difficult to reconcile how the data from the individual Mg/Ca measurements of the two species shown in Fig. 2 were combined into one single solid curve in Fig. 2 upper panel and also in Fig. 3. The red and black lines in Fig. 2, do they represent a running mean of individual data points? I suppose that individual Mg/Ca ratios (red and black dots) of the two species, where available stem from the same sample. If this is true, in many cases these ratios differ quite substantially between species while in other they are quite similar. Any explanation for the larger differences?

I also strongly recommend to provide error bars on the individual estimates for bottom temperatures that result from uncertainties in analytical procedures and calibration. While the cooling of the deep Southern Ocean is quite obvious for the begin of HS4, without knowledge about the cumulative uncertainty of absolute temperature estimates, it remains much more speculative whether at the end of the stadial deep waters warmed again or stayed more or less at the cold end well into the following stadial as indicated by comparison with NGRIP d18O record in both figures. If the latter is true, this may be taken as an argument unfavorable for the hypothesized process, except if the authors can provide a convincing argument why bottom temperature should remain very low, while AMOC and Northern Hemisphere temperature rapidly recover to interstadial conditions. In this context, it is unfortunately apparent that at the end of HS4 the largest mismatch between modeled Tdw and proxy-based temperature estimates is largest. Any reason to explain these deviations would be very helpful to accept the hypothesis in general.

3) Discussion: It would be much easier to follow the line of arguments used to explain the amplitude of atmospheric warming and CO_2 increase as a response to increased Southern Ocean deep convection if the authors could more strictly in describe the underlying processes, e.g. the direction of gas exchange and heat transfer, where it takes places with respect to the Antarctic frontal zones, etc. For example, in Fig. 4 the bottom temperature difference in modeled SO convection and no SO convection (TrS-Tr) mainly occurs in the polar and sub-Antarctic zones of the South Atlantic and western Indian Ocean sectors, while largest TrS-Tr differences in heat flux and MLD are simulated for the entire Pacific sector for the subtropical zone. In contrast, for the region covered by the proxy record in the South Atlantic sector it seems that heat flux between ocean and atmosphere is not much affected exactly in the area where the strongest signal of changes in the thermal bipolar seesaw is commonly associated with surface ocean circulation. Any explanation for this?

4) Minor items:

- lines 52 to 53: Text in parentheses (….though it is notable that there are short intervals, e.g. cooling late in interstadials, where Greenland and Antarctic temperature proxies appear to follow similar trends) Either provide reference or eliminate this remark.
- Fig 2 and caption: Please mention here or in Method section how the red and black solid lines in the lower panel were generated and explain what the solid red line in the upper panel stands for. Only the inverted black line from the lower panel, or a running mean of all estimates from both species. See comment above for Methods.
- line 132: Fig. 3 does not show any model results, can be skipped here.
- Fig. 3: Indicate letters A, B, C, and D for the different panels, according to the reference in the figure caption.
- Fig. 4 and caption: In panels C and D color code scaling is for heat flux from atmosphere to the ocean, means negative values denote heat release from the ocean to the atmosphere, which is somewhat inconsistent with the direction of argumentation in the discussion text, explaining increase in ocean to atmosphere heat flux by the stronger deep ocean ventilation, similar to what is written in the figure caption: ..ocean to atmosphere heat flux. Should be noted somewhere!

Review comments for Skinner et al.

Summary

Proxy data suggest substantial millennial climate variability during the glacial period, characterized with a "thermal bipolar seesaw". This has been linked to variations in the Atlantic Meridional Overturning Circulation (AMOC) in many studies. However, climate models with suppressed AMOC often underestimate the Southern Hemisphere warming and CO_2 increase during the Heinrich Stadial (e.g., Kageyama et al., 2013). In a previous study by Menviel et al. (2015), they proposed that this conundrum can be resolved by involving a "deepwater seesaw", i.e., the Antarctic Bottom Water (AABW) formation is strengthened when the AMOC becomes weaker. In this study, the authors claim that they find proxy evidence for a stronger AABW formation during HS4 to support the proposed idea in Menviel et al. (2015). I find this paper interesting and think that it is a useful addition to our discussion. I have listed my comments below.

General Comments

- Is a stronger AABW formation the only possibility that could lead to such a deep ocean cooling? Presumably, a weakening in the AMOC would reduce the fraction of the warmer NADW in the deep ocean such that we might also see such a cooling without any change in the AABW formation. Can you comment on this?

- With a surface warming in the Southern Ocean and likely less sea ice during HS4, this suggests less brine rejection due to reduced sea ice formation and a weaker Southern Ocean deep convection. Could you discuss any potential process that might drive a stronger AABW formation?

- The deep cooling and Antarctic warming in Fig.2 is compelling. However, it is hard to tell a causal relationship between these two lines. In general, there are many reasons that could cause the climate models to fail to simulate observations. For the underestimated Antarctic warming in climate models with suppressed AMOC, are there any other processes in addition to Southern Ocean convection that could play a role? Can you also comment on this?

Specific Comments

- (Lines 65-68): The AABW formation is modified by adding salt to the Southern Ocean rather than by enhancing heat loss in Menviel et al. (2015).

- (Lines 73-77): Based on your Fig. 4, the extra heat loss in the runs with SO convection from ocean to the atmosphere takes place roughly between 50°S and 60°S. That is the latitude range where the Circumpolar Deepwater outcrops in the Southern Ocean, and it is far from the AABW formation region. The discussion here give me the impression that you are linking the extra heat loss directly to the AABW convection.

- (Lines 134-137) Why not show the temperature directly in Fig. 4? Based on Menviel et al. (2015, their Fig.7), the warming between 50°S and 60°S appears to be associated with the upwelling of the warm Circumpolar Deepwater, which is mainly advected along isopycnals by the eddy bolus velocity (e.g., Marshall and Speer, 2012). The discussion here seems to imply that the warming is due to the enhanced ocean-to-atmosphere heat flux, which actually works to cool the sea surface.

- (Fig.4): Based on the plot of mixed layer depth, there is no convection close to Antarctica. Where is the deep convection located in this model?

- (Lines 143-163) I think I understand what you are talking about. It would greatly benefit the readers if you can draw a schematic or plot a figure to illustrate how is this happening.

References

Kageyama, M., and Coauthors, 2013: Climatic impacts of fresh water hosing under Last Glacial Maximum conditions: a multi-model study. *Clim. Past*, **9 (2)**, 935–953.

Marshall, J., and K. Speer, 2012: Closure of the meridional overturning circulation through Southern Ocean upwelling. *Nat. Geosci.*, **5 (3)**, 171–180.

Menviel, L., P. Spence, and M. H. England, 2015: Contribution of enhanced Antarctic Bottom Water formation to Antarctic warm events and millennial-scale atmospheric CO2 increase. *Earth Planet. Sci. Lett.*, **413**, 37–50.

RESPONSE TO REVIEWER COMMENTS:

Our responses are embedded in the reviewer comments below, in red italicised text. We have also highlighted changes to the accompanying revised manuscript in red.

Reviewer #1 (Remarks to the Author):
I find this paper interesting and think that it is a useful addition to our discussion. I have listed my comments below.

General Comments

- Is a stronger AABW formation the only possibility that could lead to such a deep ocean cooling? Presumably, a weakening in the AMOC would reduce the fraction of the warmer NADW in the deep ocean such that we might also see such a cooling without any change in the AABW formation. Can you comment on this?

We have considered this possibility (indeed previous studies have pointed to significant changes in the representation of NADW vs. AABW at this site); however, a key point is that the observed cooling coincides with an increase in the local radiocarbon activity, and an increase in oxygenation, both of which (though the former especially) would be hard to explain by a simple reduction of northern sourced water, since NADW would be expected to be better ventilated than AABW.

We have now added a more explicit note of this to the first paragraph of the discussion section.

- With a surface warming in the Southern Ocean and likely less sea ice during HS4, this suggests less brine rejection due to reduced sea ice formation and a weaker Southern Ocean deep convection. Could you discuss any potential process that might drive a stronger AABW formation?

This is again a good question. A simple answer to this question might be that the AABW formation rate did not really change much (our idealised model scenarios would be getting the 'right answer' for the wrong reason in this case), but rather that air-sea exchange affecting AABW precursor waters was enhanced, for example by a reduction of sea ice cover at the northerly edge of the sea ice range. However, an alternative answer to the puzzle might derive from recent work carried out by Thompson et al. (Journal of Climate, 2019). This work employed an isopycnal box model to demonstrate that the closure of the global overturning circulation (driven by continuous energy and buoyancy input) might require a spin-up of the southern abyssal cell when the flux of NADW is reduced, and the outcrop position of CDW shifts southward in response. A critical assumption of this analysis, is that brine rejection and negative buoyancy forcing remains constant/strong in the region of AABW formation, to the south. This is not implausible: despite shifts in the northward extent of the Antarctic sea ice formation and export, the main sea ice factory near Antarctica likely remained active during the last glacial period. According to the dynamical theory laid out by Thompson et al. (2019), the negative buoyancy flux in this region not need to change at all in order for a greater proportion of upwelling CDW to be modified by air-sea exchanges that impart negative buoyancy, on its way south (instead of north).

We now refer to this study in the discussion section. As noted below, we have also added a short statement that other processes may also have played an important role simulating convection, including shifting winds, and/or the opening of polynyas due to increased sub-surface warmth.

- The deep cooling and Antarctic warming in Fig.2 is compelling. However, it is hard to tell a causal relationship between these two lines. In general, there are many reasons that could cause the climate models to fail to simulate observations. For the underestimated Antarctic warming in climate models with suppressed AMOC, are there any other processes in addition to Southern Ocean convection that could play a role? Can you also comment on this?

  In the context of the last glacial millennial-scale climatic variability, the underestimated warming in Antarctica could be due to a lack of concurrent atmospheric CO2 increase (i.e. some of the AMOC shutdown experiments are performed with a constant atmospheric CO2 concentration). However, this increased atmospheric CO2 concentration would not lead to a cooling at depth.

  Several numerical modelling experiments have however shown that a high southern latitude warming can be obtained either through oceanic heat release to the atmosphere (e.g. Pedro et al., 2016; though this study also obtains only ~50% of the observed warming), or through enhanced advection of lower latitude waters towards Antarctica, for example through a strengthening of the Antarctic Circumpolar Current (ACC, e.g. Menviel et al., 2015). However, as they are both influenced by changes in surface density, enhanced deep ocean convection in the Southern Ocean and a strengthening of the ACC often occur at the same time.

  While, a negative phase of the SAM could also induce an Antarctic warming (e.g. Thompson & Salomon, 2002), the effects of changes in the magnitude and position of the westerlies could be opposite, and changes in the southern hemispheric westerlies would also impact the ACC transport and deep-ocean convection in the Southern Ocean.

  We have tried to clarify in the text that although the 'fingerprint' of convection is apparent in the data (and supported by the model), the processes leading to enhanced convection have yet to be elucidated:

  "*The association of lower temperature, higher deep ocean oxygen content, and lower radiocarbon ages in the deep sub-Antarctic Atlantic, concurrent with a temperature increase at the surface of the Southern Ocean and over Antarctica, is consistent with enhanced deep-ocean convection. Deep-ocean convection leads to heat release from the ocean to the atmosphere, thus contributing to the Antarctic warming. However, the processes leading to enhanced deep-ocean convection in the Southern Ocean during Heinrich stadials remain poorly constrained, and could involve either changes in surface buoyancy linked with changes in sea-ice cover or a strengthening/poleward shift of the southern hemispheric westerlies.*"

Specific Comments

- (Lines 65-68): The AABW formation is modified by adding salt to the Southern Ocean rather than by enhancing heat loss in Menviel et al. (2015).

Yes, this is true, but we were not referring to the model scenario forcing. The sense of the sentence was rather: "enhanced convection helps to achieve greater Antarctic warming (and CO2 rise), by increasing heat loss from the ocean to the atmosphere".

- (Lines 73-77): Based on your Fig. 4, the extra heat loss in the runs with SO convection from ocean to the atmosphere takes place roughly between 50◦S and 60◦S. That is the latitude range where the Circumpolar Deepwater outcrops in the Southern Ocean, and it is far from the AABW formation region. The discussion here give me the impression that you are linking the extra heat loss directly to the AABW convection.

In the model scenario, it would indeed appear that the rate of water mass conversion from upwelled CDW to AABW was increased. However, as noted above, in discussing the results of Thompson et al. (2019), an alternatively possibility in reality might be that the AABW formation rate did not change significantly, and instead the precursor waters for AABW were able to equilibrate with the atmosphere more completely (losing heat, and carbon, in the process), with a greater proportion of these derived from upwelled Circumpolar Deep Water (CDW).

We have now tried to address this in the discussion section, where we note that a key aspect of the mechanism at work might be a change in the proportion of upwelling CDW that loses buoyancy and contributes to AABW, rather than gaining it to resupply NADW.

- (Lines 134-137) Why not show the temperature directly in Fig. 4? Based on Menviel et al. (2015, their Fig.7), the warming between 50◦S and 60◦S appears to be associated with the upwelling of the warm Circumpolar Deepwater, which is mainly advected along isopycnals by the eddy bolus velocity (e.g., Marshall and Speer, 2012). The discussion here seems to imply that the warming is due to the enhanced ocean-to-atmosphere heat flux, which actually works to cool the sea surface.

We show the heat flux instead of the temperature, as the latter has been shown numerous times before and does not provide an indication that the warmth is sourced from the ocean interior (as opposed to incoming short-wave radiation, or outgoing long-wave radiation, for example), which is our primary concern here. Indeed, ocean-to-atmosphere heat flux works to cool the ocean: but a greater heat flux out of the ocean can be obtained, even at higher overall temperature (or indeed a smaller ocean-atmosphere temperature difference), if more heat is accessed from a thicker layer of water. A well-mixed km of water will affect the air above it far more than a thin/stratified layer will. Accordingly, the key thing is the combination of greater heat loss and deeper mixed layer penetration, as we seek to show in the figure.

- (Fig.4): Based on the plot of mixed layer depth, there is no convection close to Antarctica. Where is the deep convection located in this model?

Although the full complexity of the processes leading to convection cannotbe captured by the relatively coarse resolution model we employ, it does produce deep convection close to Antarctica. Nevertheless, we are wary of placing too much emphasis on the details of convection in the model (e.g. where and how it occurs exactly), as these are likely to be *limited by the resolution of the model, and to reflect the idealised forcing that was imposed in the simulations, rather than the processes that could have brought about convection in the real ocean. This is precisely why a main recommendation of ours is to encourage further work using more sophisticated, coupled AOGCMs.*

- (Lines 143-163) I think I understand what you are talking about. It would greatly benefit the readers if you can draw a schematic or plot a figure to illustrate how is this happening.

Though we are wary of cartoons (which can often me more misleading than anything), we have attempted to make a schematic illustration of the ideas presented here concerning shifting loci of buoyancy loss from the ocean, now included as Figure 5. We defer to editorial advice on its inclusion.

Reviewer #2 (Remarks to the Author):
Assessment: This a careful and thorough study. In general, fully-coupled simulations are best for assessing the global climate because only coupled simulations include the significant feedbacks between the ocean and the strength and position of the surface winds, but the intermediate-complexity models they use, while not ideal, are good enough to assess the broad impacts of the imposed climate forcing. I'm delighted to see another paper with specific evidence debunking the "bipolar seesaw" and the AMOC mechanism and metaphor.

Recommendation: Accept and publish.

Reviewer #3 (Remarks to the Author):
1) Introduction: Lines 50 to 58 address the time lag of a few centuries between NH cooling and the Antarctic response across climate interstadials. This is not taken up later in the discussion whether the alternative explanation in terms of thermal and gas exchange response from the deeper Southern Ocean is also in favor for such a delay. Therefore I recommend to either skip this item here in the introduction or address it later in the discussion again, for example, as an explanation why the deep ocean cooling does not cease immediately with the end of HS4.

Although we can't account for this feature, we believe it is important to accurately describe the nature of the 'bipolar seesaw' (which for us is properly a pattern, not a mechanism).

2) Methods and Results: In the supplementary information, the authors add to the existing ´calibration´ data sets new core-top data for Uvigerina sp (Table S1). However, in Fig S1 the value for the Mg/Ca ratio at the lowest temperature 0.99 °C is lacking, why?

We thank the reviewer for spotting this! We have fixed this figure.

In addition, the authors should clearly point to the fact, that the temperature range reconstructed for the time interval of interest is not covered by the temperature range of calibration, particularly not for the negative values.

This is a good point; we have added a note of this in the results section.

Furthermore, it is difficult to reconcile how the data from the individual Mg/Ca measurements of the two species shown in Fig. 2 were combined into one single solid curve in Fig. 2 upper panel and also in Fig. 3. The red and black lines in Fig. 2, do they represent a running mean of individual data points? I suppose that individual Mg/Ca ratios (red and black dots) of the two species, where available stem from the same sample. If this is true, in many cases these ratios differ quite substantially between species while in other they are quite similar. Any explanation for the larger differences?

The data were indeed combined by averaging calibrated temperature values at a given sediment depth, where more than one estimate was available. The line that is plotted is a smoothed line (spline) running through the resulting dataset.

However, in order to provide an estimate of the uncertainties in the resulting time-series we have now included a cubic spline fit to the averaged data shown in Fig. 2, with 95% confidence intervals.

Discrepancies between measurements made on two different species from the same sediment sample, that are larger than analytical uncertainties, are indeed to be expected. The reasons for such 'noise' in proxy measurements include analytical uncertainty, but this is generally not the main contributor: measurements are made on a number of individual foraminifera, which will have been bioturbated in the active sediment layer, and therefore will have a distribution of ages and taphonomic histories; there may be subtle genotype influences on chemistry that morphotype selection is blind to; there may be other influences on Mg/Ca (e.g. from carbonate chemistry, salinity, alkalinity, calcification rate…) that are poorly constrained and that differ for each species; etc… This is precisely why we have taken the (arguably bold) approach of measuring two different species in parallel: obtaining the same temperature history from both species is very unlikely to have been due to accidental biases from other factors (unless the main control on Mg/Ca in general is not T at all, but this is also rather unlikely).

We have emphasized this in the manuscript, at the end of the results section.

I also strongly recommend to provide error bars on the individual estimates for bottom temperatures that result from uncertainties in analytical procedures and calibration.

This is a good point; we have added the analytical uncertainty estimates to the presentation of the Mg/Ca results in Fig. 2, and have now included a cubic spline fit with 95% confidence intervals for the averaged deep-water temperature record (also in Fig 2).

While the cooling of the deep Southern Ocean is quite obvious for the begin of HS4, without knowledge about the cumulative uncertainty of absolute temperature estimates, it remains much more speculative whether at the end of the stadial deep waters warmed again or stayed more or less at the cold end well into the following stadial as indicated by comparison with NGRIP d18O record in both figures. If the latter is true, this may be taken as an argument unfavorable for the hypothesized process, except if the authors can provide a convincing argument why bottom temperature should remain very low, while AMOC and Northern Hemisphere temperature rapidly recover to interstadial conditions. In this context, it is unfortunately apparent that at the end of HS4 the largest mismatch between modeled Tdw and proxy-based temperature estimates is largest. Any reason to explain these deviations would be very helpful to accept the hypothesis in general.

Again, this is a good point; the lack of a strong warming at the end of HS4 had not escaped our attention. While this does provide cause for reflection, it is not obvious that a strong influence of Southern Ocean convection/water mass conversion on deep-water T (DWT) would require a rapid warming at the end of the stadial. If DWT was mainly controlled by NADW presence, then yes, this would be expected. However, if (as we are interpreting) local deep-water DWT is more strongly influenced by Southern Ocean air-sea exchange, then we might instead expect a rather gradual warming. Indeed, we would expect DWT to track the deep-water ventilation, e.g. as indicated by the B-P radiocarbon ventilation metric. This is indeed what is seen: both DWT and B-P show a rather gradual 'tailing off' after HS4, rather than an abrupt shift. The discrepancy with the idealised model scenario is not extremely worrying, because the details of the model results will depend crucially on the arbitrary forcing that is employed. The main point of the model scenarios is not to emulate the proxy records perfectly, but rather to illustrate the sense in which enhanced Southern Ocean convection affects deep-water temperature and oxygenation, in parallel with Antarctic air temperature and atmospheric CO2.

This is an important issue, and we have therefore added a note of it in the first paragraph of the discussion section.

3) Discussion: It would be much easier to follow the line of arguments used to explain the amplitude of atmospheric warming and CO2 increase as a response to increased Southern Ocean deep convection if the authors could more strictly in describe the underlying processes, e.g. the direction of gas exchange and heat transfer, where it takes places with respect to the Antarctic frontal zones, etc. For example, in Fig. 4 the bottom temperature difference in modeled SO convection and no SO convection (TrS-Tr) mainly occurs in the polar and sub-Antarctic zones of the South Atlantic and western Indian Ocean sectors, while largest TrS-Tr differences in heat flux and MLD are simulated for the entire Pacific sector for the subtropical zone. In contrast, for the region covered by the proxy record in the South Atlantic sector it seems that heat flux between ocean and atmosphere is not much affected exactly in the area where the strongest signal of changes in the thermal bipolar seesaw is commonly associated with surface ocean circulation. Any explanation for this?

We are not certain to understand the point that "heat flux between ocean and atmosphere is not much affected exactly in the area where the strongest signal of changes in the thermal bipolar seesaw is commonly associated with surface ocean circulation." It is not at all clear that any existing proxy records can constrain adequately where the largest changes in ocean-atmosphere heat flux have occurred. It is true that the model simulates strongest changes outside of the Atlantic sector, but we are not aware of any strong proxy evidence that could be used in conjunction with this to argue against the processes that operate in the model. For example, if strong signals are recorded in proxy records from the Atlantic sector, this does not mean that a stronger signal in other sectors can be ruled out.

However, we have tried to introduce some more detail on the processes at work, without overstepping the level of detail that can be justified with our methods (e.g. the simulations are not suitable for dissecting the processes of convection, since *convection is artificially stimulated as a forcing). As noted above already, we have added a note that the degree and sense of modification of upwelled CDW (in the sub-polar Antarctic) might indeed be a key factor for influencing the precursor waters of AABW, rather than changes in the region of AABW formation itself.*

4) Minor items:
- lines 52 to 53: Text in parentheses (….though it is notable that there are short intervals, e.g. cooling late in interstadials, where Greenland and Antarctic temperature proxies appear to follow similar trends) Either provide reference or eliminate this remark.

We have specified that during the later parts of interstadials both hemispheres appear to cool, and provide a citation for the alignment of Greenland and Antarctica that reveals this.

- Fig 2 and caption: Please mention here or in Method section how the red and black solid lines in the lower panel were generated and explain what the solid red line in the upper panel stands for. Only the inverted black line from the lower panel, or a running mean of all estimates from both species. See comment above for Methods.

This has been added to the figure caption, in which the erroneous reference to temperature in the bottom panel has been corrected.

- line 132: Fig. 3 does not show any model results, can be skipped here.

Fig 3 does include model outputs.

- Fig. 3: Indicate letters A, B, C, and D for the different panels, according to the reference in the figure caption.

This has been corrected.

- Fig. 4 and caption: In panels C and D color code scaling is for heat flux from atmosphere to the ocean, means negative values denote heat release from the ocean to the atmosphere, which is somewhat inconsistent with the direction of argumentation in the discussion text, explaining increase in ocean to atmosphere heat flux by the stronger deep ocean ventilation, similar to what is written in the figure caption: ..ocean to atmosphere heat flux. Should be noted somewhere!

We have corrected the error in the figure caption.

We are very grateful for all of the review comments, which have been very helpful in improving the manuscript.

Decision letter and referee reports: second round

31st Jul 20

Dear Dr Skinner,

Your manuscript titled "Southern Ocean convection amplified past Antarctic warming and CO2 rise" has now been seen by our reviewers, whose comments appear below. In light of their advice I am delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment under the open access CC BY license (Creative Commons Attribution v4.0 International License).

We therefore invite you to revise your paper one last time to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

EDITORIAL REQUESTS:

Please review our specific editorial comments and requests regarding your manuscript in the attached "CommsEarth Final revisions information checklist". Please outline your response to each request in the right hand column.

SUBMISSION INFORMATION:

In order to accept your paper, we require the files outlined in the attached "CommsEarth Final submission file checklist.pdf"

OPEN ACCESS:

Communications Earth & Environment is a fully open access journal. Articles are made freely accessible on publication under a CC BY license (Creative Commons Attribution 4.0 International License). This license allows maximum dissemination and re-use of open access materials and is preferred by many research funding bodies.

For further information about article processing charges, open access funding, and advice and support from Nature Research, please visit https://www.nature.com/commsenv/about/open-access

At acceptance, the corresponding author will be required to complete an Open Access Licence to Publish on behalf of all authors, declare that all required third party permissions have been obtained and provide billing information in order to pay the article-processing charge (APC) via credit card or invoice.

Please note that your paper cannot be sent for typesetting to our production team until we have received these pieces of information; therefore, please ensure that you have this information ready when submitting the final version of your manuscript.

Please use the following link to submit the above items:
[link redacted]
** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Joe Aslin

Associate Editor,
Communications Earth & Environment
https://www.nature.com/commsenv/
Twitter: @CommsEarth

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

I appreciate the reviewers for the insightful responses to my previous review comments. Now I am happy to recommend this paper to be accepted. This will be an important contribution to our understanding of the glacial-interglacial climate changes.

Reviewer #2 (Remarks to the Author):

I am glad that the authors have addressed the other reviewer's comments and questions. This paper is better for it.

Reviewer #3 (Remarks to the Author):

As already said in my first review the manuscript is very worth the publication in this journal, since it provides new paleo data with respect to deep ventilation in the Southern Ocean during Antarctic warming periods under glacial conditions. This "ventilation" effect is challenging the often cited ´thermal bipolar seesaw´ concept and should be published now, with all my previous comments/questions on the manuscripts satisfactorily addressed by the authors.

Response to review comments:

Reviewer #1 (Remarks to the Author):
I appreciate the reviewers for the insightful responses to my previous review comments. Now I am happy to recommend this paper to be accepted. This will be an important contribution to our understanding of the glacial-interglacial climate changes.

We are grateful for the reviewer's previous comments, and are pleased to have addressed their concerns completely.

Reviewer #2 (Remarks to the Author):
I am glad that the authors have addressed the other reviewer's comments and questions. This paper is better for it.

We thank the reviewer for their comments.

Reviewer #3 (Remarks to the Author):
As already said in my first review the manuscript is very worth the publication in this journal, since it provides new paleo data with respect to deep ventilation in the Southern Ocean during Antarctic warming periods under glacial conditions. This "ventilation" effect is challenging the often cited ´thermal bipolar seesaw´ concept and should be published now, with all my previous comments/questions on the manuscripts satisfactorily addressed by the authors.

We again thank the reviewer for their comments.