Jean-Baptiste Ladant

Yannick Donnadieu

Christophe Dumas

Laboratoire des Sciences du Climat et de l'Environnement

CE Saclay – Bâtiment 701

91191 Gif-sur-Yvette FRANCE

Email: jean-baptiste.ladant@lsce.ipsl.fr

*Links between $CO_2$, glaciation and water flow: reconciling the Cenozoic history of the Antarctic Circumpolar Current*

Response to the referees' comments

Dear editor and referees,

We thank you for the possibility to submit a revised version of our manuscript. We have tried to underline in a clearer way the two main points of our study:

1) We present another process (ice sheet waxing and waning) impacting the intensity of the Antarctic circumpolar current, which has up to now been neglected in studies investigating the formation of the ACC.
2) Based on our study as well as on previous modeling and data work, we propose a hypothesis that may explain the Eocene-Miocene evolution of the ACC and reconcile

upholders of an initiation at the Eocene-Oligocene transition as much as those advocating an initiation at the Oligocene-Miocene boundary.

We hope that this revised version will be suitable for publication in Climate of the Past.

Please note also that we have slightly modified the figure 2 of the previous version so that the oceanic current can be better spotted. Figures 4, 5 and 7 have been added or heavily modified.

Best regards,

Jean-Baptiste Ladant, on behalf of all co-authors.

Response to referee 1

*(1) The authors of this manuscript study the effect of the building of an Antarctic ice sheet on the surrounding southern ocean, in particular the possible development of a (proto)-ACC. While many studies have focused on the effects of ocean circulation changes (e.g. the development of an ACC) on ocean heat transport and ice-sheet development, this study takes a complimentary angle on these issues, with the aim to better constrain the actual development of the ACC. This is an interesting approach, and the model design seems to me reasonable.*

Thank you for noting the relevance of this approach.

*(2) However, the analysis of the results in this manuscript is way too simple in my opinion. Firm conclusions could potentially been drawn if a lot more analysis of the model results is included in the paper.*

Our choice not to include many analyses arose from the fact that the effects of the buildup of the ice sheet on the Southern Ocean in our model were excessively similar to the effects obtained by Lefebvre et al. (2012) when looking at the effects of a $CO_2$ drop on the Southern Ocean. In both cases, the colder regional conditions result in a sea-ice increase strengthening the ACC. The whole analysis was developed in detail in Lefebvre et al. (2012) and we found somewhat redundant to carry out exactly the same analysis.

Yet, it is true that from the figures displayed in the previous version of our manuscript, the links between the development of the circumpolar current and the increased sea ice formation could not be very well understood. As you and both the editor and the other reviewer suggest, we have added analyses to state more clearly our point (see below).

*(3) The main point of the paper is, that increased sea ice formation changes the meridional density structure in the Southern Ocean, which drives an ACC-like current.*

We take the opportunity of this comment to point that there are two major points in our paper. On the one hand, we show the ice sheet effects on the circumpolar current, indeed mainly attributing these to the increased sea ice and associated brine formation around Antarctica. The meridional density gradients increase, reinforcing the intensity of the circumpolar water flow (Gent et al., 2001). With regard to these links (to which could be added potential wind-driven changes, see below), we believe that the relationship between the waxing and waning of the Antarctic ice sheet and the ACC should not be put aside, especially between the Eocene and Miocene because of the variability of the Antarctic ice sheet (Holbourn et al., 2005; Miller et al., 2005a; Miller et al., 2005b; Zachos et al., 2001).

On the other hand, we formulate a plausible hypothesis that reconcile data studies pointing to an ACC onset close to the Eocene-Oligocene transition (Borrelli et al., 2014; Florindo and Roberts, 2005) with those advocating an onset at the Oligocene-Miocene boundary (Pfuhl and McCave, 2005), while being in agreement with latest geological studies (Lagabrielle et al., 2009) and other paleoclimate modeling work (Hill et al., 2013).

*(4) From the figures provided I cannot see whether this is really the case. The two (Ross- and Wedell) gyres indicated in Figure 2c, develop in areas where there is always sea ice in winter, particularly in the Tasman region (Figure 4), so I don't see why these gyres are important for the ACC flow and why they should develop? In addition, I guess that due to the buildup of an ice sheet the wind structure will change quite dramatically in some regions, this is not shown nor discussed in the paper. (The used atmospheric model might also be not sufficient to study this in detail.). The density structure shown in Figure 5 is indeed quite different for no ice sheet or a full ice sheet, but why this is, cannot be concluded from the model results shown so far.*

The gyres developing in the Tasman and Weddell seas are not stricto-sensu important for setting up the circumpolar flow. They are rather a consequence arising from the changes in the meridional density gradient, which reorganizes the circumpolar pathway. We see the development of these two gyres as an evidence of an ACC-like flow, as the reorganization of the circumpolar current in our experiments does share features with modern present-day ACC.

We do totally agree with your comments concerning the wind structure. The buildup of the ice sheets indeed changes the latter substantially. In the previous version of the manuscript, we did not include any discussion because, as you very well noted, the atmospheric resolution is quite low in FOAM and therefore, changes in the atmospheric wind structure are more complicated to study and surely not resolved enough to prove really robust.

In the revised version however, we have added a discussion about wind-related changes as well as details about the limitations due to the resolution of FOAM's atmosphere, which leads us to avoid drawing too many conclusions from this analysis (see lines 163 – 177 and Fig. 4 of the revised version).

Future work, using higher resolution models, will be able to study this processes in much more detail. Indeed, you can see on Fig. 4 of the revised manuscript, preliminary results using the LMDZ (Laboratoire de Météorologie Dynamique Zoom) AGCM in 96 x 95 x 39 resolution with the same Eocene paleogeography. The runs with LMDZ are forced with SST fields from the corresponding FOAM runs, other boundary conditions being kept identical. This clearly shows that the ice sheet leads to poleward-shifted stronger Westerlies as well as stronger polar Easterlies.

Regarding density patterns, it is true that we did not include many analyses because as said above, we felt this redundant with the work of Lefebvre et al. (2012), which shows a similar behavior of the sea ice regime although the causes invoked in their paper are different. We agree, though, that the revised version is much clearer thanks to the additional analyses we added following your suggestion. These analyses show that the modifications in the density structure of the Southern Ocean are related to major changes in the salinity gradient, which are explained by increased sea ice formation driving brine rejection. We also have added a figure showing the percentage of gain/loss of sea ice between the 560 ppm full ice sheet and ice-free Antarctica (Fig. 5 of the revised version).

To study the changes in the density structure, we used the same analyses as Lefebvre et al. 2012. We linearized the density equation $\Delta\rho = \Delta\rho_S + \Delta\rho_T$ with $\Delta\rho_T = \alpha\ \Delta T$ and $\Delta\rho_S = \beta\ \Delta S$ ($\alpha$ is the thermal expansion and $\beta$ the haline contraction) and plotted the density difference and the density difference related to salinity and temperature changes (Fig. 7 of the revised version). The main possible mechanism responsible for these salinity changes is the increase of sea ice around Antarctica, which increases brine formation and leads to the formation of very cold and saline waters. This will modulate the density gradients and so the thermohaline circulation, which strengthens the ACC (Gent et al., 2001; Hogg, 2010).
You may also refer to lines 178 – 206 of the revised manuscript.

*(5) Section 2: Models and Experiments Some information on the spinup procedure and the length of the simulations would be adequate here! Are the experiments in equilibrium? As the atmospheric model is quite low resolution, maybe a discussion about model limitations would be also in place.*

We agree that we should have added information concerning the simulations. We ran every simulation for 2000 years without flux correction or deep-ocean acceleration. We consider the experiments in quasi-equilibrium as over the last hundred years of model integration, the globally averaged ocean temperature drift on the whole water column is < 0.1°C/century in each experiment, comparable to other GCMs (e.g., Dai et al. (2005)).
We have modified the Models and Experiments section to include these information and we also have added, as suggested, a comment about FOAM limitations concerning the atmospheric part (lines 99 – 108, 163 – 165, 175 – 177).

*(6) In conclusion, I recommend the paper to be considerably revised and much more further analysis necessary before it can be published in Climate of the Past or anywhere else.*

We hope that the additional analyses and the modifications in the manuscript do match your expectations. We have tried to emphasize that our aims in this paper are to show that the ice sheet impacts on the ACC should not neglected and to provide a plausible hypothesis explaining a possible Cenozoic history of the ACC, which can reconcile the different ACC imprints seen in the data.

We also slightly expanded the Introduction section (lines 58 – 62) and slightly re-written the Method section (lines 81 – 89 and 92 – 96) and the Discussion section (lines 252 – 257).

*(7) Specific comments: Page 2399, lines 1-3: There are even earlier estimates of Drake Passage openings. In fact since 50 Ma Drake Passage seems to be opening (Eagles et al. 2003, 2006).*

Yes, we fully agree that the tectonic history of Drake Passage is very complicated. It seems clear from many studies (Eagles et al., 2006; Scher and Martin, 2006) that Drake Passage was opened for most of the Eocene, with a deepening at the latest Eocene / earliest Oligocene (Lawver and Gahagan, 2003) before a temporary closure between 29 and 22 Ma (Lagabrielle et al., 2009).

We have added references to Eagles and Jokat (2014) and Eagles et al. (2006).

*(8) Page 2401, lines 18-28: What would the authors define as a real ACC-flow? And when is it only a weak eastward transport?*

In the 560 ppm ice-free experiment, the eastward transport reaches respectively 8 and 13 Sv at Drake and Tasman passages. These values are small compared to the full ice sheet case (respectively 54 and 59 Sv) or the modern ACC in the control run (113 and 136 Sv respectively). In the previous version, we therefore used the term "eastward transport of low intensity" to qualify the ice-free transport through the gateways.

When the ice sheet builds up, there is a clear increase in the eastward transport (Table 1 and Fig. 3 of the revised manuscript) and a reinforcement of proto-Ross and Weddell gyres, which are a consequence of the strengthening of the current (see above). As these gyres do also exist in the modern ACC, the ice sheet buildup reorganizes the current in an ACC-like flow. Being fully aware of the limitations of FOAM, we do not attempt or pretend to model every feature of the modern ACC (which is even not achieved by the most comprehensive models) but we rather state that the current reorganization shares similarities with the modern ACC.

*(9) Page 2402, lines 18-25: Here it is explicitly stated that the ACC is a delicate balance between wind-driven and buoyancy driven currents, so why only focus on the density driven part?*

As you very well mentioned above, we originally decided not to focus on the wind-driven part because of the coarse atmospheric resolution of our coupled model FOAM. Such a resolution (4.5° in latitude by 7.5° in longitude) might not resolve with sufficient details the changes in the winds associated with the buildup of the ice sheet, which complicates the analyses on the atmospheric part.

Nonetheless, we have added in the revised manuscript a discussion about wind-related changes (lines 163 – 177) as well as details about the limitations due to the resolution of FOAM's atmosphere (lines 99 – 108).

Besides, bottom form stress, which is also one of the primary drivers of the ACC (Cai and Baines, 1996), is not investigated in this manuscript, as we maintain the bathymetry constant through all simulations.

*(10) Page 2405, lines 1-8: This discussion is extremely vague. The case with full ice sheet and high CO2 is also most likely inconsistent on the long term, so the sea ice distributions are unreliable. Again also the wind pattern will change, and so will the circulation.*

We agree that such high $CO_2$ is likely to provoke the melting of a substantial part of the ice sheet. However, due to the ice sheet hysteresis effect linked to the strong feedbacks (height-mass balance and albedo) associated with a large ice sheet, a significant amount of ice might still be present over the Antarctic continent (Pollard and DeConto, 2005).
Moreover, present-day ice sheet models starting with a full Antarctic ice sheet (AIS) and forced by high $CO_2$ climate fields taken from an equilibrated GCM run with appropriate conditions (i.e., the full AIS and high $CO_2$) do not simulate much reduction in the extent and volume of the Antarctic ice sheet (D. Pollard, personal communication). To significantly melt the AIS, the $CO_2$ concentration has to reach about 6 to 8 times the preindustrial atmospheric levels (D. Pollard, personal communication).
Therefore, the present test with a full ice sheet and 1120 ppm should be regarded as a sensitivity study, which further highlights the fact that $CO_2$ variations may have impacted the intensity of the circumpolar current, even with a potentially large ice sheet.
We address a small discussion about this (lines 262 – 269).

Response to referee 2

*(1) This paper reports results from a modeling study that shows continental cooling driven by ice sheet formation increases sea ice formation, thereby strengthening the ACC. The results are set in the context of numerous studies exploring the evolution of glaciation of Antarctica and the development of the ACC.*

*The paper appears to be basically sound, and the modeling approach seems reasonable.*

Thank you for noting this.

*(2) I find the analysis to be rather superficial, and this is a weakness that might preclude publication in its present form. The authors briefly address the role of the meridional density gradient as a dynamical mechanism driving the ACC, though the physic of this are not explored in any meaningful way. There is no explanation of why the ice sheet is related to the sea ice regime. Essentially, the detailed modeling work is not supported by adequate analysis.*

We agree that the analyses presented in the manuscript were not comprehensive. However, this was partly intentional because the main purpose of this manuscript is not to provide a comprehensive review and analysis of the mechanisms driving a circumpolar current during the Eocene-Oligocene. Our aim here was to present a possible mechanism (the ice sheet effects) impacting the circumpolar current, which has been up to now neglected. Paleogeographic constraints (Hill et al., 2013) and $CO_2$ variations (Lefebvre et al., 2012) had already been put forward as main factors affecting the circumpolar current intensity. Here, we show that the ice sheet buildup (and therefore possible subsequent melting) is also a first-order driver of the intensity of this current.

Starting from this, we formulate a hypothesis that may explain the temporal variations of the circumpolar current through the Cenozoic, in agreement with other studies and published data. Future data studies concerning ACC imprints and spanning the entire Eocene to Miocene sections should help resolve the history of this current.

Regarding the other analyses we have included in the revised manuscript, we kindly ask you to refer to the concerns of reviewer 1, which are essentially similar to yours. Besides, you may refer to DeConto et al. (2007) for an extensive study of ice sheet/sea ice feedbacks. Essentially, the increase in the sea ice extent derives from the regionally colder conditions (including SSTs) provided by the buildup of an ice sheet of continental scale (DeConto et al., 2007; Goldner et al., 2014).

*(3) Minor comments.*

*pg 2398, ln 7: others –> other*

*pg 2399, ln 16: colder conditions which could [be an alternate mechanism beyond] the decrease in atmospheric...*

*pg 2401, ln 3: Consistently –> Consistent*

Done

<u>Response to the editor</u>

*(1) Dear Dr Ladant,*

*your contribution has been seen by two reviewers. The reviews are rather similar. They both* *acknowledge that the modeling method used is scientifically sound, and that the results are potentially of great interest.*

Thank you for noting this. We firmly believe that our results show that the ice sheet should be equally regarded as one of the main drivers of the circumpolar current (as are paleogeographic constraints and $CO_2$ variations) during the Cenozoic.

*(2) However, both reviewers also stress that the analysis of the model output is by far too brief. I strongly suggest that you expand the result section by adding a discussion about the physical link existing between the sea ice formation, the associated disturbances in the oceanic density patterns, and the strength of the ACC. This discussion must be accompanied by a clear related figure.*

Yes, after careful reading of the reviews, we acknowledge that we should have made the analyses more complete.

We have added new analyses (please refer to the answer to reviewer 1) and have re-written or added substantial parts of the manuscript (lines 58 - 62, 81 – 89, 92 – 96, 99 – 108, 163 – 177, 178 – 206, 252 – 257, 262 – 269).

*(3) I fully understand that part of this discussion can be found in Lefebvre et al. (2012), and that your paper is an extension of this previous study which was not considering ice sheets over Antarctica. However, the present contribution must be understandable by itself, without jumping back and forth in the published literature.*

Thank you for this. We indeed think our study to be complimentary to the one of Lefebvre et al. (2012), as it invokes the same physical mechanisms (i.e., sea ice expansion leading to circumpolar current reinforcement), although the cause is different. We have therefore added new discussions concerning the wind-driven part (and the associated limitations due to FOAM atmospheric resolution) and we have extended the analyses on the density changes linked to the expansion of sea ice.

We simply wanted here to point out that the ice sheet should not be neglecting when investigating the Cenozoic history of the circumpolar current (especially under the warmer climate of the Eocene and Oligocene when the Antarctic ice sheet was smaller than today). This led us to build a hypothesis to try to reconcile apparently contradicting data regarding the timing of initiation of the circumpolar current. Because the late Eocene and Oligocene is a time of ice sheet variability of high amplitude (and possibly of $CO_2$ variations) and complicated tectonic history in the Southern Ocean, we infer, based on our and other modeling results (Hill et al., 2013; Lefebvre et al., 2012), a possible temporal evolution of the circumpolar current, which is found to be in relatively good agreement with available data.

*(4) From my own reading, one point appears unclear to me. You prescribed ice sheet over Antarctica, but you did not mention how you prescribe it: how do you define the size and, most importantly, the shape of the ice sheet for the various simulations ?*

This is an interesting question, thank you.

Our ice sheet sizes and shapes derive from unpublished runs using the ice sheet model GRISLI (Ritz et al., 2001). These ice sheet runs were obtained following the same methodology as detailed in Ladant et al. (2014).

Essentially, for this paper, we have chosen the ice sheets to cover a broad range of possible sizes for each atmospheric $CO_2$. However, at 1120 ppm, studies have shown that only small ice sheets, which do not reach the Antarctic coastline, may have existed (e.g., Miller et al. (2005b)). Similarly, 560 ppm is under the large-scale glaciation $CO_2$ threshold (DeConto and Pollard, 2003; Gasson et al., 2014); therefore prescribing a small or a medium ice sheet is not coherent.

Regarding the shape, ice sheets over Antarctica always build up the same way. Ice nucleates on the highest peaks of the continent and then expands, first in East Antarctica and then on the Western shores. That is why, even if the unpublished runs used to prescribe the ice sheets differ from one $CO_2$ to another, the geometry of two ice sheets of comparable volume but different $CO_2$ is very similar (see Fig. 1 of the revised manuscript).

*(5) It might be also interesting to discuss a bit more the importance (or not) of the presence of an ice sheet, compared to the previous study by Lefebvre et al. (2012) which was neglecting the role of continental ice.*

This is a fair question. It would definitely be interesting to compare the relative contribution to local cooling and oceanographic changes of $CO_2$ and ice sheet buildup. Here, however, we did not hazard very in-detail comparisons because we use another Antarctic topography and the depth of the two gateways is different. In this study, we have chosen to limit ourselves to the impact of the ice sheet, regardless of other contributors to local changes in the circumpolar current (such as tectonics).

Yet, the question of the evolution of the circumpolar current remains a big challenge, so future studies using higher resolution models and exploring systematically the relative impact of ice sheet, topography and $CO_2$ may be a positive step forward in our comprehension of the evolution of the ACC.

This study is still the first showing a clear impact of the ice sheet buildup on the circumpolar current in a warmer world. Future studies investigating the paleo-ACC should therefore take into account the evolution of the ice sheet as we show that the latter has the potential to initiate a strong circumpolar current.

*(6) In summary, I recommend you to consider all the reviewers questions and my own points when preparing the revised manuscript.*

We have tried to answer every question and comment raised by both reviewers and you. We hope that these answers as well as the revised version of our manuscript will match your expectations and the standards of Climate of the Past.

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