Clim. Past, 10, 1957–1966, 2014
www.clim-past.net/10/1957/2014/
doi:10.5194/cp-10-1957-2014

Climate of the Past
Open Access

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

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Received: 25 April 2014 – Published in Clim. Past Discuss.: 22 May 2014
Revised: 5 September 2014 – Accepted: 19 September 2014 – Published: 14 November 2014

Abstract. The timing of the onset of the Antarctic Circumpolar Current (ACC) is a crucial event of the Cenozoic because of its cooling and isolating effect over Antarctica. It is intimately related to the glaciations occurring throughout the Cenozoic from the Eocene–Oligocene (EO) transition ($\approx$ 34 Ma) to the middle Miocene glaciations ($\approx$ 13.9 Ma). However, the exact timing of the onset remains debated, with evidence for a late Eocene setup contradicting other data pointing to an occurrence closer to the Oligocene–Miocene (OM) boundary. In this study, we show the potential impact of the Antarctic ice sheet on the initiation of a strong proto-ACC at the EO boundary. Our results reveal that the regional cooling effect of the ice sheet increases sea ice formation, which disrupts the meridional density gradient in the Southern Ocean and leads to the onset of a circumpolar current and its progressive strengthening. We also suggest that subsequent variations in atmospheric CO_2, ice sheet volumes and tectonic reorganizations may have affected the ACC intensity after the Eocene–Oligocene transition. This allows us to build a hypothesis for the Cenozoic evolution of the Antarctic Circumpolar Current that may provide an explanation for the second initiation of the ACC at the Oligocene–Miocene boundary while reconciling evidence supporting both early Oligocene and early Miocene onset of the ACC.

1 Introduction

As the largest of all currents, the Antarctic Circumpolar Current (ACC) has been studied for decades because of its non-negligible role in major climatic changes of the Cenozoic, notably at the Eocene–Oligocene transition (Kennett, 1977). If the opening of the Tasman Passage between Australia and Antarctica is relatively well constrained with progressive deepening between 35 and 30 Ma (Stickley et al., 2004), there are still numerous uncertainties in the timing of the opening of Drake Passage (Barker and Burrell, 1977; Lawver and Gahagan, 2003; Livermore et al., 2007; Scher and Martin, 2006), with earliest estimates pointing toward the early Eocene (Eagles and Jokat, 2014; Eagles et al., 2006). Consequently, the evolution of the ACC through time between the Eocene and the Miocene remains unclear. Some studies have proposed an onset in the earliest Oligocene (Florindo and Roberts, 2005; Katz et al., 2011), while other evidence tends to point to initiation in the late Oligocene or early Miocene (Lyle et al., 2007; Pfuhl and McCave, 2005; Scher and Martin, 2008). In a modeling approach, Toggweiler and Bjornsson (2000) found that the opening of Drake Passage had a cooling effect over southern high latitudes, but DeConto and Pollard (2003b) showed that possible changes in ocean heat transport due to gateways opening only had a limited impact on the Eocene–Oligocene Antarctic glaciation. This opinion was subsequently corroborated by Huber and Nof (2006). More recently, Hill et al. (2013) have argued that paleogeographic constraints prevented ACC initiation until the late Oligocene, while Lefebvre et al. (2012) investigated the effect of a decrease in atmospheric CO_2 concentration on the onset of the ACC and found that this current was not triggered by CO_2 typical of the late Eocene, hence delaying the current's initiation to the late Oligocene under colder climatic conditions.

Here, we study the impact of the Antarctic ice sheet (AIS) growth at the Eocene–Oligocene boundary on the potential initiation of the ACC. The AIS has the potential to provide regionally colder conditions which could drive the ACC initiation or reinforcement in the same way as the decrease in

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atmospheric CO_2 (Lefebvre et al., 2012) or tectonic forcings (Hill et al., 2013; Sijp et al., 2011). We propose that the combined variations of the atmospheric CO_2 level, of the Antarctic ice sheet size and of the tectonic evolution of the Southern Ocean from the Eocene to the Miocene may have modulated the intensity of the circumpolar current, making the issue of a unique onset of the ACC more complex and probably obsolete.

2 Models and experiments

In this study, we use the mixed-resolution general circulation model (GCM) FOAM (Fast Ocean Atmosphere Model) to realize coupled runs investigating the ice sheet growth effect on the oceanic circulation around Antarctica at the Eocene–Oligocene boundary. The atmospheric component runs on a 4.5° by 7.5° grid with 18 vertical levels. It is a modified version of the parallelized NCAR's CCM2 (Community Climate Model v2) model so that the atmospheric physics is equivalent to CCM3. The highly efficient ocean component is dynamically similar to the Modular Ocean Model of GFDL (Geophysical Fluid Dynamics Laboratory) (Jacob, 1997). It runs on a 1.4° by 2.8° grid with 12 of the 24 vertical levels in the upper 1000 m. The sea ice model uses the thermodynamics of NCAR's CSIM (Community Sea Ice Model) 2.2.6. FOAM has been used to successfully simulate present-day climate (e.g., Zhang et al., 2005) as well as paleoclimates (Chaboureau et al., 2012; Dera and Donnadieu, 2012; Poulsen et al., 2003).

In this paper, we aim to decipher the impact of a growing ice sheet on the Southern Ocean circulation and particularly whether it impacts a potential circumpolar current. Recent studies have shown that the continental-scale threshold for the Eocene–Oligocene Antarctic ice sheet is close to 700–900 ppm (DeConto and Pollard, 2003a; Gasson et al., 2014). We therefore set up GCM runs with atmospheric CO_2 concentrations of 560 ppm (2× preindustrial atmospheric levels – hereafter PAL), 840 ppm (3× PAL) and 1140 ppm (4× PAL), the latter being close to pre-transition CO_2 levels (Pagani et al., 2011). From unpublished runs following the methodology described in Ladant et al. (2014), we have prescribed different ice sheet sizes over Antarctica (Fig. 1), which were chosen to cover a broad range of ice volume. Note that for the 560 ppm simulations, we did not prescribed any small ice sheet over Antarctica as the CO_2 levels are well below the threshold for a large-scale glaciation. Similarly, the maximum ice sheet size at 1120 ppm is small compared to the large maximum ice sheet size prescribed at 840 ppm or the full ice sheet prescribed at 560 ppm. This is because small ephemeral glaciation may have existed during the Eocene under CO_2 concentrations higher than 1000 ppm (Tripati et al., 2005) but they did not reach the Antarctic coastline (Miller et al., 2005), justifying the ice sheet sizes we use here (Fig. 1). The corresponding approximate ice volume prescribed for each ice sheet simulation can be found in Table 1.

Table 1. Water transport through the Drake and Tasman gateways for each simulation.

CO_2 (ppm)	Ice sheet size (approximate ice volume in 10^6 km^3)	Flow intensity at Drake Passage (Sv)	Flow intensity at the Tasman Passage (Sv)
1120	Ice free	6	10
	Very small (3.5)	9	14
	Small (6)	10	15
840	Ice free	8	11
	Small (6)	14	18
	Medium (11)	29	38
	Large (16)	35	46
560	Ice free	8	13
	Large (15)	42	49
	Full (25)	54	59

The paleogeography used here is modified after the early Oligocene paleogeography used by Lefebvre et al. (2012). Both southern passages are opened with a mean depth of 1600 m, in agreement with already intermediate to deep gateways around 34–33 Ma (Eagles et al., 2006; Stickley et al., 2004), and the topography of Antarctica is obtained by isostatically removing the present-day ice sheet (Fig. 1). The solar constant is reduced to 1361 W m^{-2} and the Earth orbit has the following parameters (DeConto et al., 2007): eccentricity = 0.05; obliquity = 24.5°; perihelion in January. Other boundary conditions are kept at modern values. Simulations are averaged over the last 50 years of equilibrated 2000-year-long runs, without any flux corrections or spinup procedure in the deep ocean; during the last 100 years of model integration, the globally averaged ocean temperature drift is < 0.1 °C century^{-1}. In the following, given the coarse atmospheric resolution of FOAM, we acknowledge that results concerning potential atmospheric changes should be treated with caution. We hope to be in position to replicate those results in the near future with a higher-resolution model such as IPSL-CM5 (Institut Pierre-Simon Laplace - Climate Model 5) (Kageyama et al., 2013). In spite of this limitation, FOAM remains a very efficient tool, both in terms of computational time, which enables us to test a broad range of initial conditions, and in terms of the results obtained in the Southern Ocean in the control simulation described in Lefebvre et al. (2012). This simulation yields realistic results when compared to observations and IPCC-AR4 (Intergovernmental Panel on Climate Change - 4th Assessment Report)-coupled simulations with 113 Sv at Drake Passage and 136 Sv at the Tasman Passage for the entire water column.

3 Results

Consistent with Lefebvre et al. (2012), the intensity of the ice-free Antarctic water flow at the Drake and Tasman passages in our simulations reaches very low values for the high

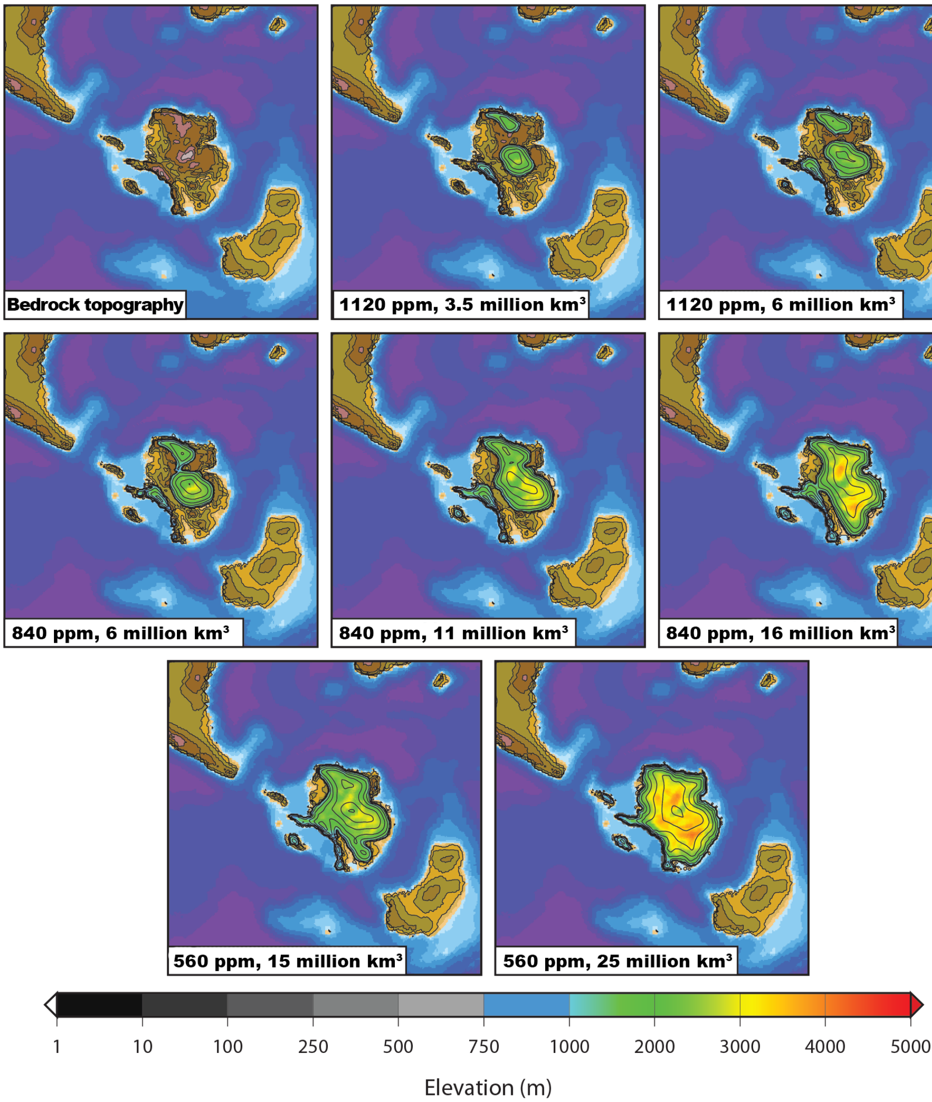

Figure 1. Bedrock topography of Antarctica and the different ice sheets prescribed at 1120, 840 and 560 ppm. Note that the different ice sheets are derived from unpublished runs for each CO_2 value, which results in a different ice sheet shape and height for each CO_2 value. The 6 million km^3 ice sheet at 1120 ppm is, hence, different from the 6 million km^3 ice sheet at 840 ppm. Yet, because ice expands very similarly regardless of the atmospheric pCO$_2$, both 6 million km^3 ice sheets are similar in shape and height. The ice sheet volume is given to ease comparisons with Table 1 of the paper.

atmospheric CO_2 concentrations typical of the late Eocene (Table 1). Interestingly, for both 2 and 3 times PAL, the ice sheet effect on the flow intensity is clear, whereas the presence of ice at 4 times PAL only has a very weak effect. Indeed, at 1120 ppm of CO_2, the water transport remains close to 10 Sv both at the Drake and Tasman passages, regardless of the amount of ice present over the continent (Table 1). At 3 times PAL, there is a gradual water transport increase as the ice sheet grows. This growth results in an increase in the zonal flow intensity, which doubles at each ice growth except in the case of the last ice sheet size. At 2 times PAL, the increase is even stronger for the two prescribed ice sheets. From an initial 8 Sv (also at Drake Passage), the transport reaches 42 Sv with a large ice sheet and 54 Sv for the full ice sheet. In all simulations, the trend in the evolution of the flow intensity calculated across the Tasman Passage is similar to the one described at Drake Passage, likely reflecting the onset of a continuous circumpolar current.

Profound changes in ocean circulation occur between the ice-free experiments and the ice sheet runs (Fig. 2). We will focus on the 560 ppm simulations, the average CO_2 threshold required to grow a full Antarctic ice sheet (Gasson et al., 2014). In the initial ice-free run, there is no strong continuous circumpolar flow around Antarctica. Some weak eastward transport of water occurs at the Drake and Tasman gateways (Table 1). After crossing the Tasman Passage, surface waters

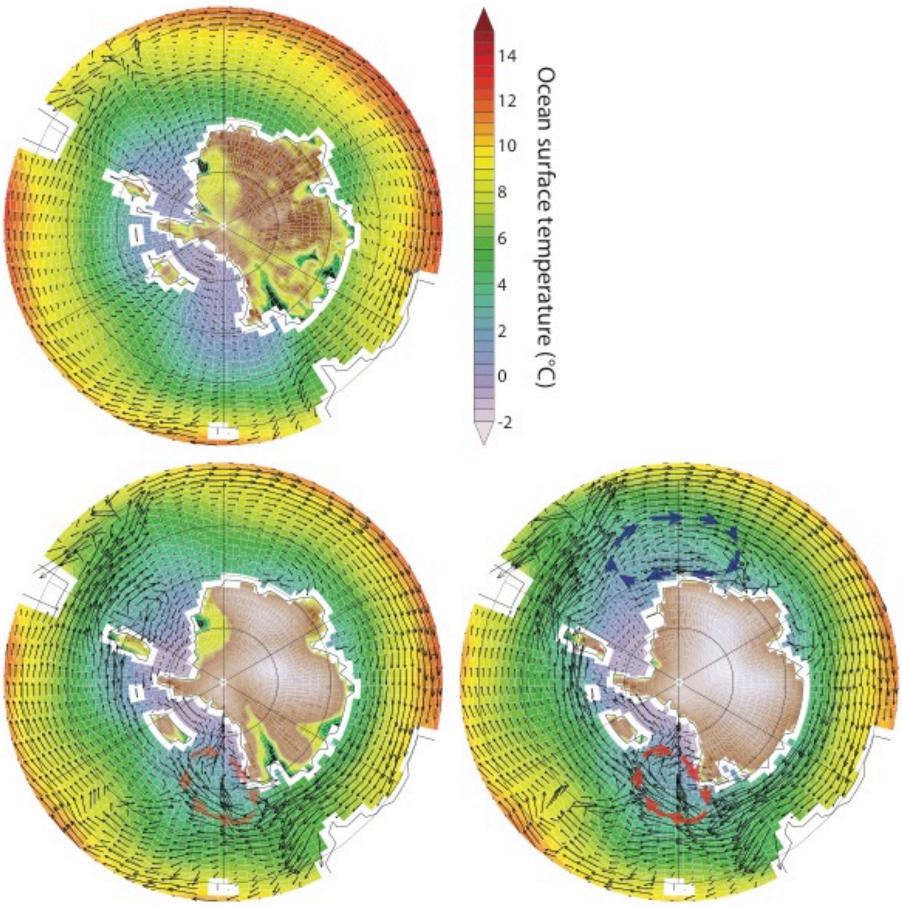

Figure 2. Surface (upper 75 m) ocean currents' reorganization and temperature associated with the growth of the Antarctic ice sheet at 560 ppm; ice-free Antarctica (top), with a large ice sheet (bottom left) or a full ice sheet (bottom right). Proto-Ross and Weddell gyres are indicated in red and blue, respectively. Note the strengthening of the proto-Ross Gyre in the full ice sheet case, indicated by a deeper shade of red in the bottom right image.

are deflected northward to join the South Pacific gyre, as previously noted by Hill et al. (2013). Only a small part of this proto-Humboldt Current effectively crosses Drake Passage. The progressive buildup of the Antarctic ice sheet reinforces the flow through the Drake and Tasman passages and enables the formation of a rather strong continuous circumpolar current. As a consequence, a proto-Ross Gyre forms in the South Pacific Ocean, as well as a proto-Weddell Gyre in the South Atlantic Ocean, once a fully grown ice sheet is established. With the full ice sheet, the proto-Ross Gyre is also reinforced along with the flow intensity around Antarctica (Fig. 2). The formation of these gyres also makes the case for a reorganization of oceanic currents – following the ice sheet buildup – into an early analogue of the modern ACC.

The vertical structure of water transport provides further support for this hypothesis. Zonal fluxes of water at cross-sectional areas located at the Drake and Tasman gateways (Fig. 3) reveal that the progressive ice sheet growth and subsequent feedbacks enable a circulation of waters around Antarctica that is similar to – although weaker than – the modern circulation. When no ice is present on the continent, there are only very weak eastward fluxes across the gateways. When an ice sheet of large size has grown, water transport through the Drake and Tasman passages increases dramatically and the water starts to be significantly advected eastward on the whole water column. With the full ice sheet, transport intensity increases all around Antarctica to reach up to half of preindustrial intensity at the Drake and Tasman passages (Table 1).

The main driving mechanism of the ACC has been subject to intense debate these past decades. Munk and Palmen (1951) were the first to propose that bottom topography could balance the eastward wind stress, while Stommel (1957) invoked wind stress curl through Sverdrup transport. Other studies have demonstrated the large impact of winds (e.g., Gnanadesikan and Hallberg 2000) and of buoyancy forcing (e.g., Gent et al. 2001). Therefore, it is likely that the ACC is driven by a complex balance between wind forcing, thermohaline-driven circulation and bottom topography (Cai and Baines, 1996).

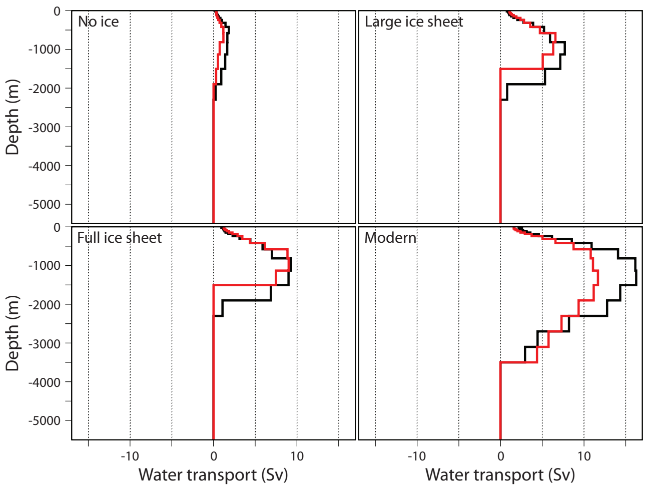

Figure 3. Zonal eastward water transport through cross-sectional areas located at the Drake (red) and Tasman passages (black) for the 560 ppm simulations for **(a)** ice-free Antarctica; **(b)** Antarctica with a large ice sheet; **(c)** Antarctica with a full ice sheet; and **(d)** for the modern Antarctica of the control simulation (Lefebvre et al., 2012).

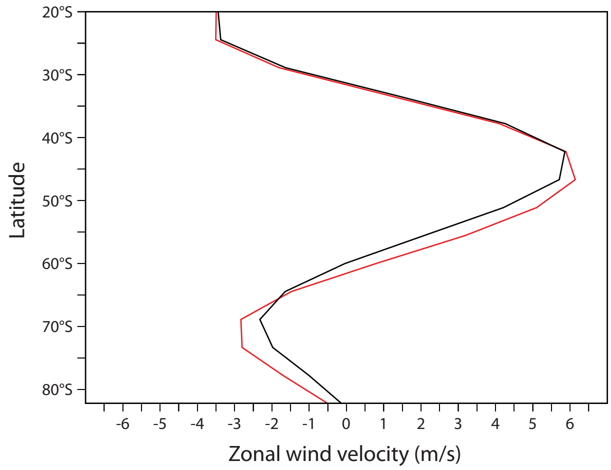

Figure 4. Zonally averaged wind velocity between 80° S and 20° S for the 560 ppm ice-free simulation (black curve) and with a large ice sheet (red curve).

Here, we do not investigate the changes related to bottom topography, and we are limited in our analysis of the wind-related changes because the atmospheric resolution of FOAM is too coarse to draw firm conclusions (7.5° in longitude by 4.5° in latitude). Nevertheless, when ice expands at 560 ppm, the westerlies (i.e., the main atmospheric driver of the ACC) strengthen and the latitudinal position of the maximum wind stress migrates poleward slightly (Fig. 4). This trend is yet to be confirmed using models with a higher atmospheric resolution, but stronger westerlies would result in a stronger circumpolar current. Additionally, close to Antarctica, the wind structure changes significantly due to the ice sheet buildup because of the links between katabatic winds and polar easterlies (Goodrick et al., 1998; Parish et al., 1994). In our simulations, the easterlies blowing around Antarctica are strengthened due to the stronger katabatic winds associated with the growing ice sheet. Again, although the atmospheric resolution of FOAM limits the extent of this analysis, the wind-related changes point to a reinforcement of the intensity of the circumpolar current linked to the ice sheet.

Moreover, the initiation of the Antarctic ice sheet has been shown to greatly enhance regional sea ice formation (DeConto et al., 2007; Goldner et al., 2014). Sea ice can impact the thermohaline circulation because its formation process releases massive amounts of salt that creates cold and very salty waters known as brines. Here, we mainly attribute the development of this proto-ACC to the increase in sea ice caused by Antarctic glaciation. Fig. 5 shows the winter sea ice extension for the 560 ppm ice-free and full ice sheet simulations. The percentage of gain or loss in sea ice shows that sea ice increases all around the continent (mean winter sea ice cover is extended by more than 75 %; see Fig. 5), notably in the modern location of the Ross and Ronne–Filchner ice shelves and in the Atlantic and Indian sectors of the Southern Ocean. In addition, the meridional density gradient increases notably between the full ice sheet simulation and the ice-free run (Fig. 6), with the ocean structure changing from a well-stratified state to steeper isopycnals reflecting a much more destratified state, especially between 80° S and 55° S. By separating the relative contributions of temperature and salinity to the density changes, we show that the salinity is the primary factor explaining the density difference (Fig. 7). Therefore, we suggest that the increased sea formation drives an enhanced creation of cold and salty waters through brine rejection (see also Lefebvre et al., 2012). The steeper meridional density gradient then reinforces the thermohaline circulation and, consequently, the circumpolar current (Gent et al., 2001; Hogg, 2010).

In any case, although the detailed explanation of the incredibly complex relationship between every component impacting the physics of the ACC has witnessed spectacular steps forward these past decades, a satisfactory and complete theory is still lacking. The aims of this paper are certainly not to provide such a theory but rather to show that the ice sheet effects on the Southern Ocean structure should not be neglected but considered as a primary driver of the evolution of the ACC through the Cenozoic. Indeed, due to enhanced thermohaline circulation related to sea ice increase (Gent et al., 2001) and possible reinforcement and poleward displacement of the westerlies, the Antarctic ice sheet has the potential to modulate the intensity of the circumpolar current, as have tectonics (e.g., Sijp et al., 2011; Hill et al.,2013) or atmospheric CO_2 (Lefebvre et al., 2012).

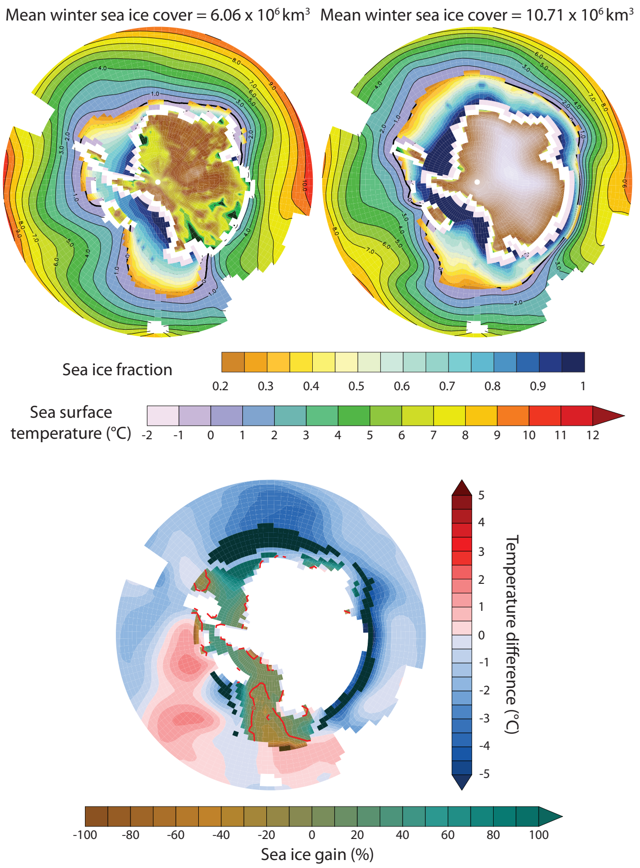

Figure 5. Sea ice extent (top), mean winter sea ice cover for the 560 ppm ice-free (left) and full ice sheet (right) simulations, and (bottom) percentage of gain/loss of sea ice overlaying SSTs (sea surface temperatures) anomaly (560 ppm full ice sheet minus 560 ppm ice-free case). Dark green color indicates areas where sea ice appeared due to colder conditions (e.g., in the South Atlantic and Indian Ocean), and dark brown color indicates areas where sea ice disappeared. The red contour is the zero line of the percentage of sea ice gain.

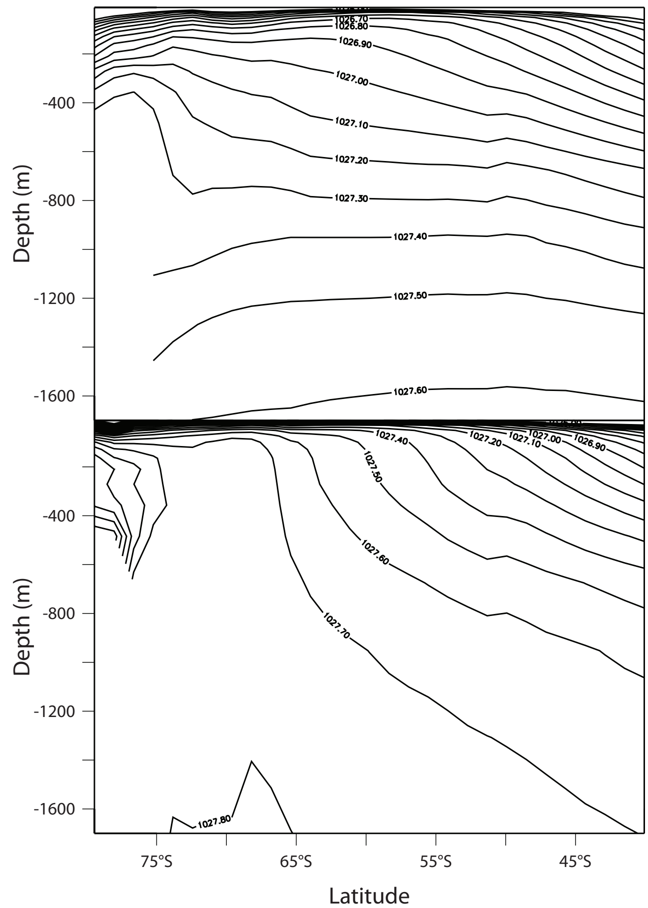

Figure 6. Zonally averaged seawater density profile for the 560 ppm (top) ice-free and (bottom) full ice sheet simulations.

4 Discussion

Our results highlight the effects of the Antarctic glaciation on a proto-ACC mainly through extended sea ice formation. Transport through the Drake and Tasman passages in our 560 ppm full ice sheet simulation is similar to the 560 ppm Rupelian (i.e., late Eocene/early Oligocene paleogeography with a glaciated Antarctica) control simulation of Hill et al. (2013). Interestingly, they do not attribute this transport to the development of a proto-ACC. Their conclusion is easily conceivable as the flow through the Drake and Tasman passages in their simulations is already similar prior to the Antarctic glaciation (see Hill et al., 2013; Rupelian control vs. Rupelian noAIS simulation). Indeed, contrary to other studies (DeConto et al., 2007; Goldner et al., 2014) and the present one, they do not find a significant sea ice increase induced by the Antarctic glaciation, which, in our results, is the main driver of the onset and further strengthening of a proto-ACC. Many studies have now shown that the existence of the ACC was not required to trigger Antarctic glaciation and that the prominent driver was likely to be the abrupt decrease in atmospheric CO_2 (DeConto and Pollard, 2003b; Huber et al., 2004; Sijp et al., 2011). In our simulation, the glaciation triggers the development of a rather strong circumpolar current, which supports the initiation of a proto-ACC as soon as the late Eocene/early Oligocene as a feedback to the buildup of the Antarctic ice sheet induced by CO_2 fall.

Our results are in agreement with numerous existing records. Scher and Martin (2006) have proposed that the increase in ε_{Nd} values at ODP (Ocean Drilling Program) sites 1090 and 689 (in the Atlantic sector of the Southern Ocean) at around 41 Ma reflects an influx of Pacific shallow waters into the Atlantic (also noted by Diester-Haass and Zahn, 1996), requiring a shallow to intermediate Drake Passage (Eagles et al., 2006; Lagabrielle et al., 2009). Though the flux through Drake Passage is low (around 10 Sv), our ice-free simulations are consistent with a Pacific-to-Atlantic

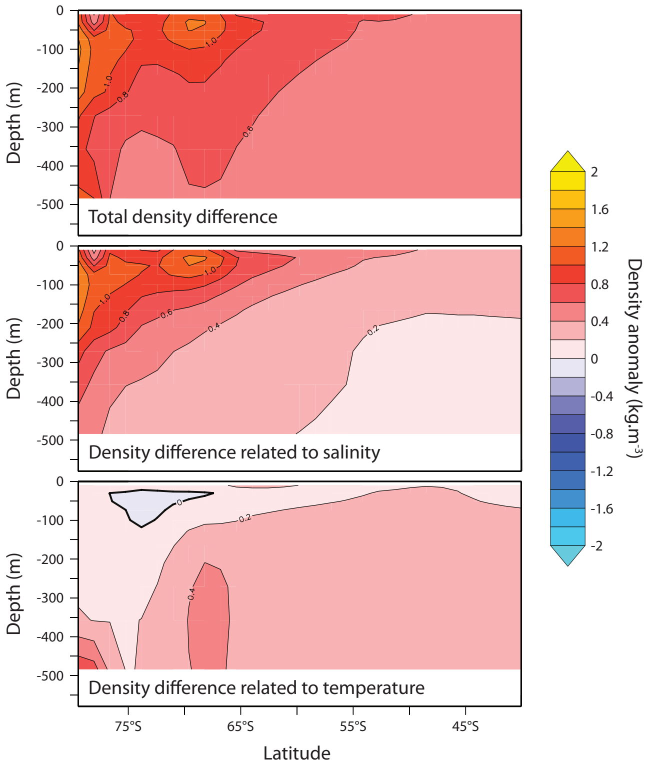

Figure 7. Total density anomaly (top) and density anomaly related to (middle) salinity and (bottom) temperature between the 560 ppm full-ice and ice-free cases. To compute the part of the total density related to salinity and temperature, we linearize the density equation (Lefebvre et al., 2012): $\Delta\rho_L = \Delta\rho_S + \Delta\rho_T$, with $\Delta\rho_T = \alpha\Delta T$ and $\Delta\rho_S = \beta\Delta S$ (α is the thermal expansion and β the haline contraction). Total ($\Delta\rho$) minus linearized ($\Delta\rho_L$) density leads to a very small difference (not shown).

water path as soon as Drake Passage opened, regardless of the CO_2 concentration.

Major Southern Hemisphere tectonic reorganizations occur close to the Eocene–Oligocene boundary, with the opening and progressive deepening of the Tasman Gateway (Lawver and Gahagan, 2003; Stickley et al., 2004) and the deepening of Drake Passage (Eagles et al., 2006; Lawver and Gahagan, 2003; Livermore et al., 2007). In addition, the Antarctic glaciation cools the continent and the surrounding ocean, leading to an increase in sea ice formation (DeConto et al., 2007; Goldner et al., 2014; Houben et al., 2013). Our results support the development of a proto-ACC of moderate intensity following the buildup of the ice sheet, roughly coeval with the EO (Eocene–Oligocene) transition onset of the ACC suggested by, e.g., Latimer and Filippelli (2002), Diekmann et al. (2004) and more recently Borrelli et al. (2014).

Some studies propose a later onset of the ACC. For example, Pfuhl and McCave (2005) analyze sediment grain size from South Tasman Rise (ODP Leg 189) and, based on the size increase around 23.9 Ma, conclude that there was an intensification of deep-water currents related to the deepening of Drake Passage and the initiation of the ACC. Lyle et al. (2007) use sediments from an upper Oligocene to Holocene piston core to place the onset of the ACC between 25 and 23 Ma. These findings are not necessarily at odds with the results of this study, which favors an earlier initiation of a proto-ACC. Indeed, this current, in our simulations, only reaches up to half of the modern day intensity, and, therefore, estimates of the onset of the ACC at the Oligocene–Miocene (OM) boundary might in fact represent another increase in the proto-ACC intensity (as well as possible modifications of the pathway) under tectonic reorganizations such as a further deepening of Drake Passage and progressive widening of the Tasman Gateway (e.g., Hill et al., 2013). An alternative solution is the possibility that the proto-ACC which was set in place in the late Eocene slows or shuts down during the Oligocene because of tectonic changes. Lagabrielle et al. (2009) show that the connection between the Pacific and Atlantic Ocean at Drake Passage faced a constriction at its northern limit between approximately 29 and 22 Ma, likely impacting the ocean circulation. Therefore, the initiation of the ACC at the Oligocene–Miocene might just be a reappearance or a restrengthening of a prior proto-ACC.

Moreover, Lefebvre et al. (2012) report a strong sensitivity of the ACC to atmospheric carbon dioxide concentration. To test the possibility that subsequent variations in Oligocene–Miocene pCO_2 (Zhang et al., 2013) affected the intensity of the proto-ACC, we carried out another simulation with the same full ice sheet as in the 560 ppm simulation but with a CO_2 concentration of 1120 ppm. Although a full ice sheet case is likely not to be consistent with such high CO_2 concentrations, the hysteresis effect (due to height–mass balance and albedo feedbacks) associated with a full ice sheet substantially impacts the CO_2 concentration required to melt the ice sheet (Pollard and DeConto, 2005). Even if they do not properly take into account the albedo feedback, Pollard and DeConto (2005) show that at roughly 900 ppm, a large ice sheet over Antarctica is still present (their Fig. 2). As the albedo feedback is of primary importance in the CO_2 glaciation threshold (Ladant et al., 2014), we can infer that a large ice sheet may remain perennial even at 1120 ppm of CO_2. Interestingly, compared to the 560 ppm full ice sheet experiment, the proto-ACC transport decreases markedly by roughly a factor of 3 at both the Drake (from 54 to 17 Sv) and Tasman (from 59 to 22 Sv) passages because the rise in atmospheric CO_2 counterbalances the impact of the ice sheet by providing warmer conditions that limit the extension of sea ice formation.

We can then hypothesize that the coupled effect of ice sheet and CO_2 could have favored times of a fairly strong proto-ACC (e.g., at the EO transition) but the successive variations in atmospheric pCO_2 and possible subsequent melting of some parts of the Antarctic ice sheet might have provoked a return to a much weaker circumpolar current. Additionally, the complex tectonic evolution of Drake Passage

(Lagabrielle et al., 2009) has surely impacted the proto-ACC intensity. The variations in atmospheric CO_2 concentration, Antarctic ice sheet extent and Southern Ocean tectonics are therefore crucial to understanding the evolution of the ACC through the Cenozoic. They can also be invoked to reconcile upholders of an EO initiation of the ACC (Borrelli et al., 2014; Diekmann et al., 2004; Latimer and Filippelli, 2002) and upholders of an OM initiation (Lyle et al., 2007; Pfuhl and McCave, 2005) by providing a mechanism for an EO strengthening of the circumpolar current as well as for an OM reinforcement. To our knowledge, no study has yet analyzed material spanning both the EO and the OM transitions in search for ACC initiation. Hence, future studies should work on resolving this issue to provide a continuous record of potential ACC imprints and help test our hypothesis concerning the ACC evolution.

5 Conclusions

Since Kennett's hypothesis of an ACC control on the major Antarctic glaciation at the EO transition, the timing of its initiation has been a matter of debate. Due to the complex tectonic evolution of the Drake and Tasman passages, reconstructing the full history of the Southern Ocean is still quite complicated. In this study, we show that the progressive growth of the ice sheet at the EO boundary leads to the initiation of a proto-ACC of up to half of modern-day transport. The main mechanism invoked to explain this rise involves increased sea ice formation around Antarctica consecutive to the glaciation (DeConto et al., 2007; Goldner et al., 2014), which modifies the meridional density gradient and leads to a stronger circumpolar current (Lefebvre et al., 2012). Possible changes related to the wind structure might also play a role, although the coarse atmospheric resolution of FOAM does not allow us to draw robust conclusions. These findings are in favor of an ACC onset close to the EO boundary but do not preclude studies invoking a later onset or reinforcement of the ACC. Indeed, we have shown that a rise in atmospheric CO_2 after the EO transition (Pearson et al., 2009) reduces the intensity of this proto-ACC. Additionally, possible waxing and waning of the ice sheet during the Oligocene seen in $\delta^{18}O$ (Wade and Pälike, 2004) and sea level records (Miller et al., 2005) as well as paleogeographic changes (Hill et al., 2013) and glacial-isostatic-adjustment-induced ocean changes due to the ice sheet buildup (Rugenstein et al., 2014) are also likely to have had a great influence on the intensity of this circumpolar flow. Possible shutdown or slowdown of the ACC between approximately 29 and 22 Ma has also been suggested due to the temporary constriction of Drake Passage (Lagabrielle et al., 2009) and can be invoked to reconcile this apparent discrepancy in the timing of the ACC: after a period of shallow circulation in the middle to late Eocene (Scher and Martin, 2006), the first onset of the circumpolar current would have occurred close to the EO boundary (Borrelli et al., 2014; Katz et al., 2011; Latimer and Filippelli, 2002) following Antarctic glaciation and before a period of possible variations in its intensity under changes in pCO_2, ice sheet size and tectonics; this development would have ended with a period of progressive slowdown (Lagabrielle et al., 2009). The Oligocene–Miocene boundary would then mark the second onset of the ACC (Lyle et al., 2007; Pfuhl and McCave, 2005), predating the evolution towards its modern features (Dalziel et al., 2013; Heinrich et al., 2011).

Acknowledgements. We thank Yves Godderis for editorial handling and suggestions that greatly improved this manuscript. Two anonymous reviewers are also acknowledged for relevant comments from which this paper benefited greatly. We are grateful to Vincent Lefebvre for his help with the simulations. Pierre Sepulchre and Didier Paillard are thanked for insightful discussions, and we also thank the CEA/CCRT for providing access to the HPC resources of TGCC under the allocation 2014-012212 made by GENCI. This research was funded by a CEA PhD grant CFR.

Edited by: Y. Godderis

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