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Paleogeographic controls on the onset of the Antarctic circumpolar current

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[1] Development of the Antarctic Circumpolar Current (ACC) during the Cenozoic is controversial in terms of timing and its role in major climate transitions. Some propose that the development of the ACC was instrumental in the continental scale glaciation of Antarctica and climate cooling at the Eocene/Oligocene boundary. Here we present climate model results that show that a coherent ACC was not possible during the Oligocene due to Australasian paleogeography, despite deep water connections through the Drake Passage and Tasman Gateway and the initiation of Antarctic glaciation. The simulations of ocean currents compare well to paleoenvironmental records relating to the physical oceanography of the Oligocene and provide a framework for understanding apparently contradictory dating of the initiation of the ACC. We conclude that the northward motion of the Australasian land masses and the reconfiguration of the Tasman Seaway and Drake Passage are necessary preconditions for the formation of a strong, coherent ACC. **Citation:** Hill, D. J., A. M. Haywood, P. J. Valdes, J. E. Francis, D. J. Lunt, B. S. Wade, and V. C. Bowman (2013), Paleogeographic controls on the onset of the Antarctic circumpolar current, *Geophys. Res. Lett.*, *40*, 5199–5204, doi:10.1002/grl.50941.

1. Introduction

[2] Today, the Antarctic Circumpolar Current (ACC) is the dominant circulation feature of the Southern Ocean, extending from the surface to the ocean floor and connecting the Atlantic, Pacific, and Indian Ocean basins. The modern ACC has a volume transport of ~130 Sv ($130 \times 10^6\,\mathrm{m^3\,s^{-1}}$), making it the largest of all ocean currents [*Barker and Thomas*, 2004]. The surface flows peak at the latitudes of the circumpolar gateways and are consistently strong and coherent throughout all longitudes (see Figure 4a).

[3] The conventional paradigm is that the ACC developed as a result of the opening of the two Southern Ocean gateways (Tasman Seaway and Drake Passage) to deep waters [e.g., *Kennett*, 1977; *Zachos et al.*, 1996]. The opening of the Tasman Seaway to intermediate and deep waters occurred progressively between 35.5 and 30.2 Ma [*Stickley et al.*, 2004], approximately coincident with the abrupt cooling across the Eocene-Oligocene transition at 33.9 Ma. However, the predominance of cosmopolitan marine microfossils in the seaway seems to preclude this, representing the initiation of a thermally isolating ACC [*Stickley et al.*, 2004]. In contrast, the timing of the opening of the Drake Passage is not widely agreed upon. Estimates for the timing of the gateway opening range from as early as 50 Ma in the early Eocene [*Eagles et al.*, 2006; *Scher and Martin*, 2006; *Livermore et al.*, 2007] to 26 Ma in the late Oligocene for shallow to intermediate water exchange [*Barker and Thomas*, 2004] and as late as ~22 Ma in the earliest Miocene for deep water circulation through the gateway [*Lawver and Gahagan*, 2003; *Lyle et al.*, 2007].

[4] Micropaleontological results from sites around the Tasman Seaway indicate that a proto-Leeuwin current transported warm Indian Ocean waters and dominated flow after the deepening of the Australo-Antarctic Gulf and prior to 30 Ma [*Huber et al.*, 2004; *Stickley et al.*, 2004; *Bijl et al.*, 2011]. Additionally, paleoclimate modeling has questioned the potential for gateway openings to act as a trigger for the growth of an ice sheet on East Antarctica, suggesting instead that it was secondary to a reduction in atmospheric CO_2 concentration [e.g., *DeConto and Pollard*, 2003; *Huber et al.*, 2004; *Sijp et al.*, 2011]. This is further supported by proxy records showing a significant reduction in atmospheric CO_2 during the Eocene, followed by a rapid decline at the Eocene-Oligocene transition [*Pearson et al.*, 2009; *Pagani et al.*, 2011]. CO_2 decline has also recently been linked with the initiation of the ACC within the FOAM climate model [*Lefebvre et al.*, 2012]. However, the timing of the development of the ACC does not seem to correspond well to CO_2 changes. The role of paleogeographic change on the initiation of the ACC has not been properly assessed, particularly after the initial opening of circumpolar gateways. Here we present novel paleoclimate model simulations, using the HadCM3L climate model, with appropriately varying paleogeographic boundary conditions to address this question.

2. Model and Experiments

[5] To investigate the role of circumpolar gateways and the glaciation of Antarctica on the onset of a strong, coherent ACC, we examine the results from a set of paleoclimate model experiments using the UK Met Office fully coupled Atmosphere-Ocean General Circulation Model, HadCM3L [*Cox et al.*, 2001]. This is a version of HadCM3 [*Gordon et al.*, 2000] with reduced resolution in the ocean component, down from 1.25° × 1.25° to 3.75° in longitude and 2.5° in latitude. This requires some changes to the coefficients in

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Table 1. Key Paleogeographic Parameters for Each Simulation

Simulation Name	Antarctic Glaciation	Drake Passage	Tasman Gateway	Australian Continental Paleolatitudes (°S)
Rupelian$^{\text{closedDrake}}$	No	Closed	Open	22.5–55
Rupelian$^{\text{noAIS}}$	No	Open	Open	22.5–55
Rupelian$^{\text{Control}}$	Yes	Open	Open	22.5–55
Chattian	Yes	Open	Open	27.5–52.5
Preindustrial	Yes	Open	Open	12.5–37.5

the diffusion scheme, to the Mediterranean outflow parameterizations [*Cox et al.*, 2001], and the removal of the island of Iceland [*Jones*, 2003]. With these adjustments the results are close to both the higher-resolution model and observations, particularly in the Southern Hemisphere [*Jones*, 2003].

[6] The results presented here represent a suite of five different HadCM3L simulations for three different time periods, the early Oligocene (Rupelian; 33.9–28.4 Ma), the late Oligocene (Chattian; 28.4–23.0 Ma), and the preindustrial era (Preindustrial; c.1850). As well as the standard early Oligocene simulation (Rupelian$^{\text{Control}}$), a further two simulations testing the sensitivity of the ACC to the presence of Antarctic glaciation (Rupelian$^{\text{noAIS}}$) and the opening of the Drake Passage (Rupelian$^{\text{closedDrake}}$) within this Stage are presented. These simulations have been run for multiple model centuries (>1500 model years) to allow, as much as possible, an equilibrium state to be reached. Paleogeographic boundary conditions for the Rupelian and Chattian simulations are derived from the early (33 Ma) and late (26 Ma) Oligocene reconstructions of *Markwick* [2007], with the key paleogeographic features listed in Table 1 and the global bathymetric reconstructions shown in Figure 1. The Rupelian$^{\text{noAIS}}$ has identical boundary conditions to Rupelian$^{\text{Control}}$, except for the removal of the ice over the Antarctic continent, with the Rupelian$^{\text{closedDrake}}$ being identical to Rupelian$^{\text{noAIS}}$ except for the introduction of a land bridge between the Antarctic Peninsula and South America. In order to isolate the impact of paleogeography, atmospheric carbon dioxide concentrations within all the Oligocene simulations are kept at twice preindustrial levels (560 ppmv), a reasonable value throughout this interval [*Pagani et al.*, 2005; *Pearson et al.*, 2009]. All other boundary conditions remain as in the Preindustrial simulation.

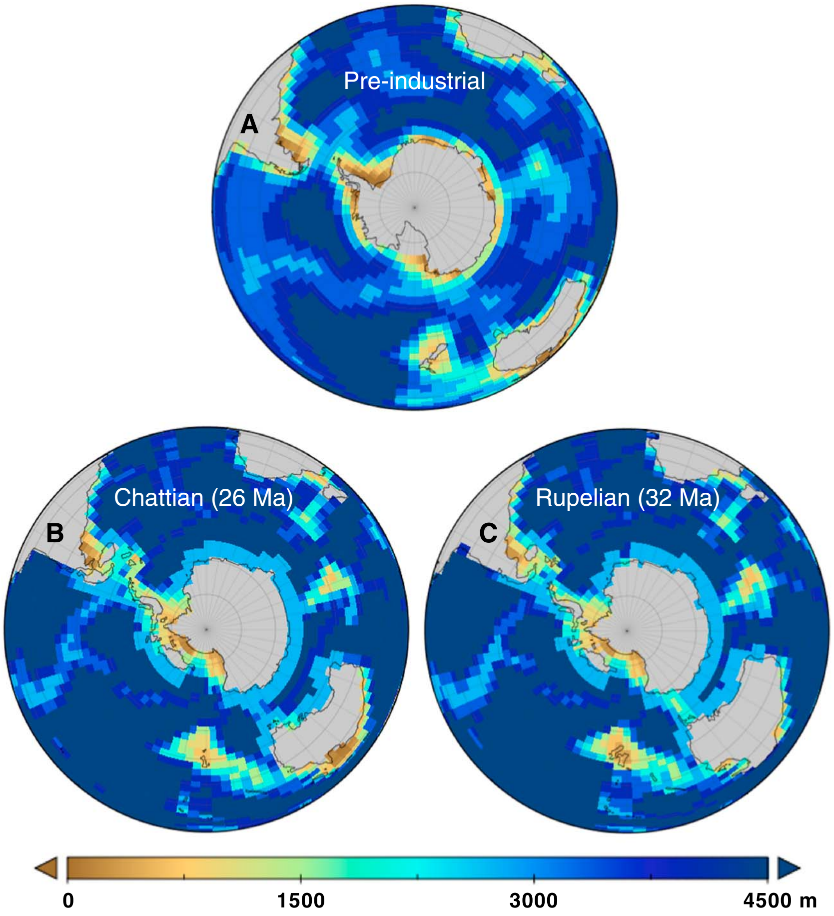

Figure 1. (a) Preindustrial era, (b) 33 Ma Rupelian, and (c) 26 Ma Chattian paleobathymetric reconstructions used within the HadCML model. The Rupelian$^{\text{closedDrake}}$ simulation uses Rupelian paleogeography with a closed Drake Passage (see Figure 2e).

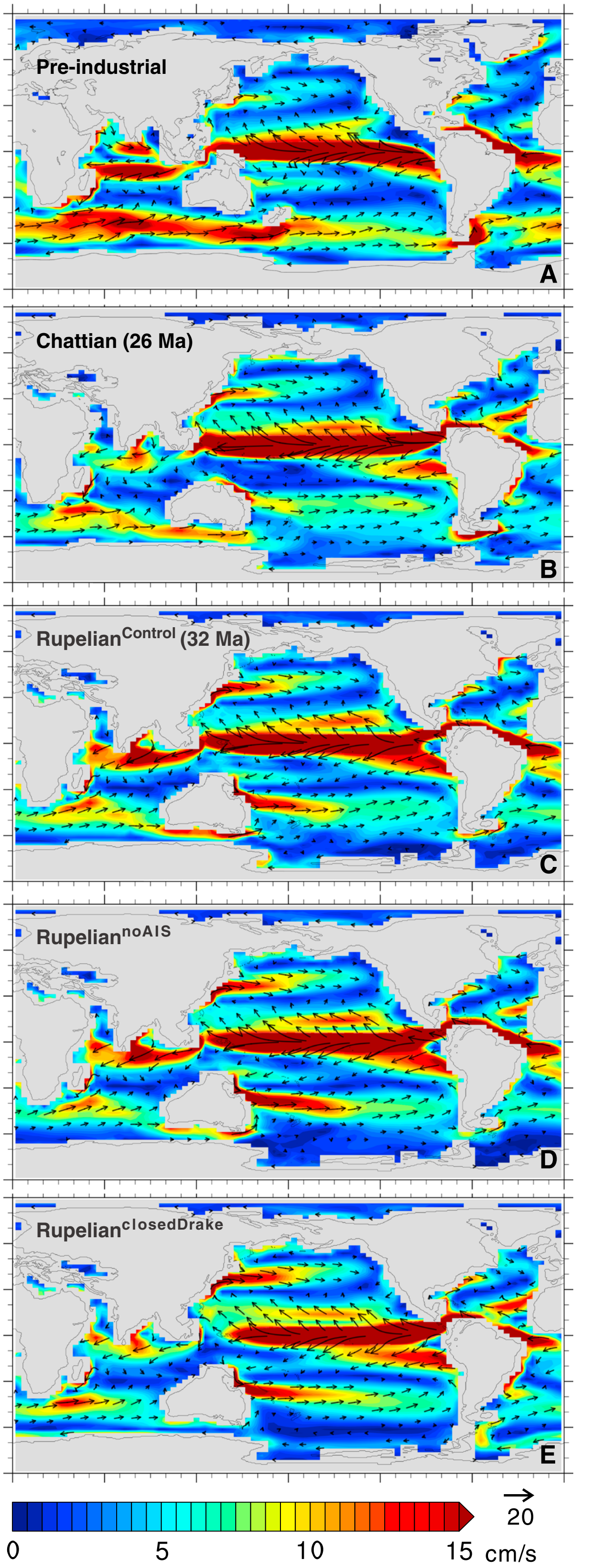

Figure 2. Global ocean surface currents in the (a) Preindustrial, (b) Chattian, (c)Rupelian$^{\text{Control}}$, (d) Rupelian$^{\text{noAIS}}$, and (e) Rupelian$^{\text{closedDrake}}$ simulations.

3. Model Results

[7] Prior to the opening of the Drake Passage, circulation in the Southern Ocean forms two distinct gyres, one in the Pacific Ocean sector of the Southern Ocean and one spanning the Atlantic and Indian Ocean sectors (cf., *Huber and Nof* [2006], where the Tasman Gateway was closed). The two gyres are only connected by weak flows through the Tasman Seaway (Figure 2e). The opening of the Drake Passage causes the breakdown of the gyres and introduces significant Easterly flows through both the Drake Passage (45 Sv) and the Tasman Seaway (increased from 25 Sv to 75 Sv). However, a modern ACC is not formed as surface currents are deflected northward on the eastern side of the Australian continent, with the main flow through the Pacific Ocean sector at significantly lower latitudes than today. This means that the majority of the returning surface waters do not enter the passage, but are deflected to form a stronger than modern proto-Humbolt current and south Pacific gyre (Figure 2d).

[8] The presence of a continental-scale Antarctic ice sheet introduces a stronger proto-Ross Sea gyre and causes significant change in the regional oceanography of the southwest Pacific. The presence of the Antarctic ice sheet increases the pressure contrast between the continental interior and the Southern Ocean, increasing both continental winds, with the introduction of major katabatic flow, and Southern Ocean winds. This in turn increases the wind stress on the surface of the ocean and leads to greater maximum surface currents through both the gateways (Figures 2c versus 2d). However, it does not significantly impact total zonal flow through the Tasman Gateway or the Drake Passage (Table 2) or the main flow through the Pacific Ocean sector (Figures 2c versus 2d). Unlike other modeling studies [*DeConto et al.*, 2007], sea ice increases are modest, with small increases in winter sea ice extent in West Antarctica and east of the Tasman Gateway. Recent paleotopographic reconstructions of Antarctica suggest that West Antarctica may have been a terrestrial landmass prior to glaciation [*Wilson et al.*, 2012]. This would remove the narrow West Antarctic seaways in existing topographic reconstructions and could lead to a small increase in ice volume and some enhancement of the impact of Antarctic glaciation.

[9] A number of important paleogeographic changes occurred in Australasia between the Rupelian and Chattian stages. The Australian continent moved northward, widening the Tasman Seaway, whilst the flooding of the northern section of the continent also widened the Indonesian Gateway [*Heine et al.*, 2010]. This movement coincided with a deepening of the Tasman Seaway by up to 1200 m [*Lawver and Gahagan*, 2003; *Brown et al.*, 2006]. The New Zealand microcontinent also moved northward and deepened (by 220 m in the paleogeographic reconstruction) between the Rupelian and Chattian stages [cf., *Sutherland et al.*, 2010]. These paleogeographic changes produce significant changes in ocean circulation in the Pacific and in the Pacific sector of the Southern Ocean. The structure of the South Pacific subtropical gyre simplifies, such that the waters for the proto-East Australian Current are sourced from the widened Indonesian Gateway. Increased zonal flow through a wider and deeper Tasman Seaway and a deepening of the paleobathymetric barrier provided by the New Zealand microcontinent means that the eastward flow through the

Table 2. Flow Through Southern Ocean Gateways and Pacific Sector for Each Simulation

Simulation Name	Drake Passage Total Zonal Flow (Sv)	Tasman Seaway Total Zonal Flow (Sv)	Southernmost High Surface Flow (> 50 mm/s) in Pacific (°S)
Rupelian$^{\text{closedDrake}}$	0	25.81	48.75
Rupelian$^{\text{noAIS}}$	44.66	74.46	51.25
Rupelian$^{\text{Control}}$	42.75	64.68	53.75
Chattian	91.32	93.65	56.25
Preindustrial	124.1	146.8	66.25

South Pacific is more diffuse, significantly reducing the areas of low surface velocity in the Southern Ocean. This enables significant increases in the flow through the Drake Passage (Table 2). Thus, the changes in paleogeography between the Rupelian and the Chattian provide a significant step toward a modern ACC. However, the main flow through the South Pacific remains at a much lower latitude than today, and the modern, strong, coherent ACC flow through the Pacific sector of the Southern Ocean has yet to be formed (Figures 2b versus 2a). Throughout all these Oligocene simulations overall Southern Hemisphere heat transports change very little, although paleogeographic changes slightly alter the partition between oceanic and atmospheric transport (Figure 3).

[10] The opening of the Drake Passage is obviously an important precondition, but merely opening this gateway and the Tasman Seaway is insufficient to form a modern ACC (Figure 2d versus 2e), as peak surface zonal currents remain at 40°S well north of the circumpolar gateways (Figure 4d). The glaciation of Antarctica causes a reorganization of the ocean currents around the continent, but has little impact on the ACC (Figures 2c versus 2d; Figure 4c). The changing paleogeography through the Oligocene seems to provide a significant step toward the formation of the modern ACC. Peak zonal surface flow has shifted to nearly 60°S and is now coincident with the widened circumpolar gateways (Figure 4b), although even in the Chattian simulation this transition is not complete as flow is slower and much of the flow is still outside the latitudes of the gateways. The impact of paleogeography on the flow rate of the ACC (Table 2) seems to be at least as important as any plausible reduction in CO_2 [*Lefebvre et al.*, 2012], although the model dependency of these conclusions have yet to be quantified.

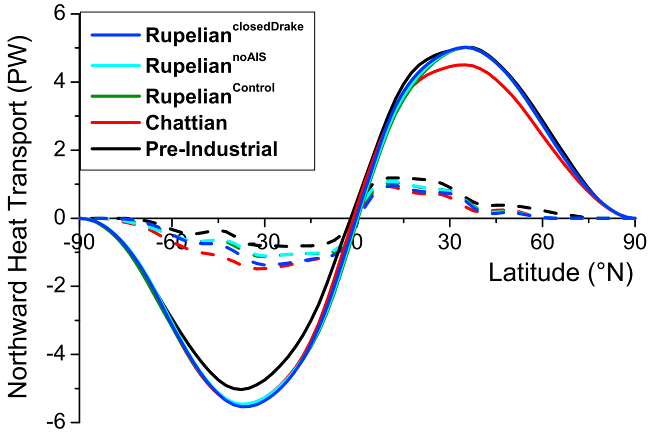

Figure 3. Zonal mean total (solid line) and oceanic (dashed line) northward heat transports for each of the simulations.

4. Consistency Between Data and Models

[11] The Rupelian$^{\text{closedDrake}}$ and Rupelian$^{\text{noAIS}}$ simulations show that as soon as the Drake Passage opened, significant easterly flows could be established, even without Antarctic glaciation or a strong circumpolar current. The most detailed tectonic studies of the Drake Passage region suggest that there may have been routes for water exchange, at least in surface waters, from as early as the middle Eocene (45 Ma). However, a continuous intermediate to deep water channel through the gateway was probably not open until sometime between 34 and 30 million years ago [*Livermore et al.*, 2007]. These results agree well with Eocene Neodymium records, which show increasing influence of Pacific-sourced water in the South Atlantic from approximately 41 Ma [*Scher and Martin*, 2006]. Both the data and the models seem to show that significant flows of Pacific water into the Atlantic were established as soon as there was a route through the Drake Passage during the late Eocene (Figure 2d).

[12] Ocean circulation in the Rupelian$^{\text{Control}}$ simulation matches data from integrated analyses of Tasman Seaway marine cores and key features of the regional currents, inferred from plankton biogeography [*Stickley et al.*, 2004; *Houben et al.*, 2013] and climate model simulations [*Huber et al.*, 2004]. Agreement in the regional circulation patterns includes a northward deflection of flow out of the gateway, a strong proto-Ross Sea gyre, and strong eastward flow at ~50°S in the South Pacific (Figure 2c). The Rupelian$^{\text{noAIS}}$ simulation indicates that much of this local structure was due to the glaciation of Antarctica. Prior to this there was no Ross Sea gyre and the flow through the Tasman Seaway was entirely deflected northward along the Australian coastline (Figure 2d). These changes in regional circulation may explain the changes in sedimentation observed on the New Zealand microcontinent, where a significant erosional event occurs in the early Oligocene [*Carter et al.*, 2004]. During the early Oligocene, a large proportion of Southern Ocean surface waters were sourced from the warmer regions of the world's ocean. The Pacific, Indian, and Atlantic Ocean all had greatly enhanced southerly flow in the Southern Hemisphere (Figure 2c), through strong western boundary currents (the proto-East Australian, East Madagascar, and Brazil currents, respectively).

[13] Carbon isotopes of benthic foraminifera from multiple water depths and ocean basins suggest that the four-layer vertical structure and heterogeneity of the modern ocean developed in the early Oligocene in response to the development of the ACC [*Cramer et al.*, 2009; *Katz et al.*, 2011]. Our model results do show a change in Atlantic Ocean structure in the early Oligocene, particularly a strengthening of Antarctic sourced water, although this does not appear to be the same as inferred by *Katz et al.* [2011]. However, carbon isotopes are not a simple tracer of water masses, and direct

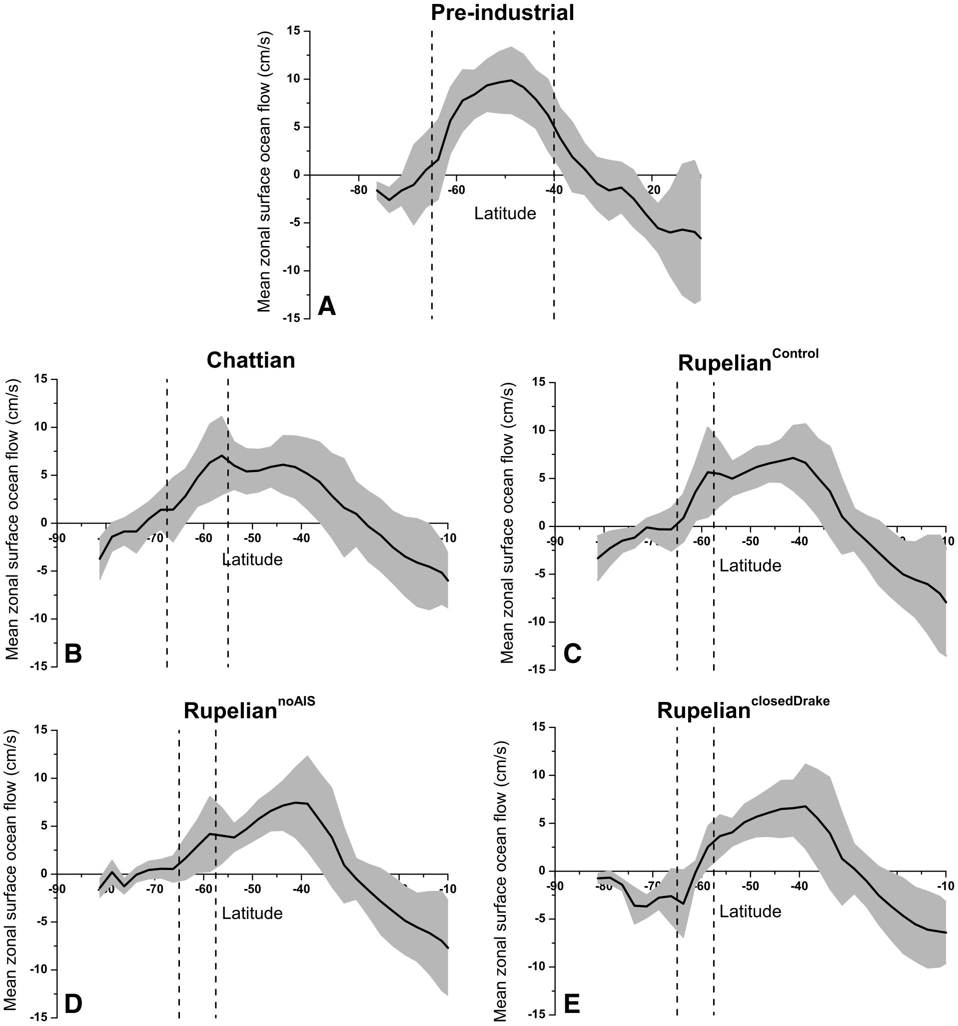

Figure 4. Southern Hemisphere mean zonal surface ocean flow for (a) Preindustrial, (b) Chattian, (c) Rupelian$^{\mathrm{Control}}$, (d) Rupelian$^{\mathrm{noAIS}}$, and (e) Rupelian$^{\mathrm{closedDrake}}$ simulations. Shading shows range of values, while dashed vertical lines show latitudes of circumpolar gateways.

comparison of these simulations and isotopic data is not possible. Recent studies have shown that gateway changes and the initiation of Antarctic glaciation could have had a significant impact on ocean nutrient cycles and marine ecosystems [*Pagani et al.*, 2011; *Houben et al.*, 2013], suggesting the impact of paleogeographic change could be even greater than can be simulated with this model.

[14] Marine core records from the Atlantic, Indian, and south-west Pacific sectors of the Southern Ocean have been studied in order to assess the overall current strengths and water-mass properties during the onset of the ACC [*Pfuhl and McCave*, 2005]. The 21 different marine records in this study provide evidence for the homogenization of circumpolar water masses and significant increases in ocean velocity at ~23.2 Ma (~23.95 Ma on the timescale of *Cande and Kent* [1995]). The proximity of this to the start of the Mi-1 glacial episode suggests that it may have been a significant event in the global climate. These model results show a much greater than modern exchange of surface waters between the subtropical gyres and the circumpolar currents, particularly in the Pacific sector, in all the simulations up to and including the Chattian simulation of 26 Ma (Figures 2b–2e versus 2a).

[15] The one major region of the Southern Ocean missing from the *Pfuhl and McCave* [2005] analysis is the central Pacific sector, which is a key location in these simulations for understanding the timing of the final onset of the ACC. However, subsequent drilling of 40 million year old central Pacific oceanic crust, formed in the path of the present-day ACC, provides an ideal record from which to trace this onset. At this site, SP-14A (presently located at 134°W), evidence for current activity was only found in sediments younger than 25 Ma, with indications for a gradual increase in current strength [*Lyle et al.*, 2007]. This agrees well with these model experiments with little or no flow before the Chattian simulation at ~26 Ma (Figure 2b).

5. Summary and Conclusions

[16] The onset of the ACC has often been linked with the opening of the Tasman Seaway and Drake Passage gateways and the glaciation of Antarctica [*Kennett*, 1977; *Zachos et al.*, 1996). Simulations of the Rupelian and Chattian using the HadCM3L climate model suggest that neither gateway opening nor Antarctic glaciation was sufficient to initiate the ACC and that strong, coherent flow through the Pacific sector of

the Southern Ocean was only established sometime after ~26 Ma. The simulations of ocean circulation provide a good match to much of the data that have been used as evidence for the initiation of the ACC. Southern Ocean water mass studies from circumpolar marine cores suggest the establishment of a strong, coherent ACC shortly after the time intervals being modeled [*Pfuhl and McCave*, 2005]. While data from the key region of the Pacific sector of the Southern Ocean also agree well with the lack of local flow up to and including the Chattian at 26 Ma [*Lyle et al.*, 2007].

[17] While the opening of the Drake Passage and Tasman Seaway are essential preconditions, they did not necessarily lead to the establishment of a modern style ACC, even after the establishment of the Antarctic ice sheets. Australasian paleogeography during the Rupelian was sufficient to maintain a different configuration of Southern Ocean surface currents, with much weaker than modern flows through the Tasman Seaway and Drake Passage gateways and disjointed zonal flow in the Pacific sector. The accuracy of Oligocene paleogeographic reconstructions is a crucial boundary condition for determining the exact timing and cause of the onset of a strong, coherent ACC.

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