

Eocene circulation of the Southern Ocean: Was Antarctica kept warm by subtropical waters?

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Received 15 February 2004; revised 28 July 2004; accepted 4 October 2004; published 18 December 2004.

[1] Near the Eocene's close (~34 million years ago), the climate system underwent one of the largest shifts in Earth's history: Antarctic terrestrial ice sheets suddenly grew and ocean productivity patterns changed. Previous studies conjectured that poleward penetration of warm, subtropical currents, the East Australian Current (EAC) in particular, caused Eocene Antarctic warmth. Late Eocene opening of an ocean gateway between Australia and Antarctica was conjectured to have disrupted the EAC, cooled Antarctica, and allowed ice sheets to develop. Here we reconstruct Eocene paleoceanographic circulation in the Tasmanian region, using (1) biogeographical distributions of phytoplankton, including data from recently drilled Ocean Drilling Program Leg 189 sites and (2) fully coupled climate model simulations. We find that the EAC did not penetrate to high latitudes and ocean heat transport in the region was not greater than modern. Our results do not support changes in "thermal isolation" as the primary driver of the Eocene-Oligocene climatic transition. *INDEX TERMS*: 1620 Global Change: Climate dynamics (3309); 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312, 4504); 4267 Oceanography: General: Paleoclimatology; *KEYWORDS*: ocean heat transport, Paleogene oceans, Antarctic glaciation

Citation: Huber, M., H. Brinkhuis, C. E. Stickley, K. Döös, A. Sluijs, J. Warnaar, S. A. Schellenberg, and G. L. Williams (2004), Eocene circulation of the Southern Ocean: Was Antarctica kept warm by subtropical waters?, *Paleoceanography*, 19, PA4026, doi:10.1029/2004PA001014.

1. Introduction

[2] A turning point in the evolution of climate from an early Cenozoic "Greenhouse" to a modern "Icehouse" was the sudden, and apparently transient, emplacement of significant ice volume on Antarctica at the beginning of the Oligocene [Miller *et al.*, 1987; Zachos *et al.*, 1996; Lear *et al.*, 2000]. During most of the Eocene, proxies reveal that climate was warm at high latitudes in both hemispheres and significant ice accumulation did not exist [Zachos *et al.*, 1993; Markwick, 1998; Zachos *et al.*, 2001; Greenwood and Wing, 1995]. The Eocene-Oligocene transition (from ~42 to 30 Myr) is marked by stepwise patterns of cooling [Zachos *et al.*, 2001; Mackensen and Ehrmann, 1992; Feary *et al.*, 1991; Lear *et al.*, 2000; Dallai *et al.*, 2001; Wolfe, 1994], changes in ocean productivity [Diester-Haass and Zahn, 2001; Salamy and Zachos, 1999] and by profound biotic

change [cf. Berggren and Prothero, 1992]. The earliest Oligocene is marked by apparent slight increases in seasonality [Ivany *et al.*, 2000], a rapid increase in Antarctic glacial volume to roughly modern total ice volume [Miller *et al.*, 1987; Mackensen and Ehrmann, 1992; Barker *et al.*, 1999; Lear *et al.*, 2000; Billups and Schrag, 2003], and an abrupt increase in productivity of the world oceans associated with a global drop in the carbonate compensation depth of >1 km [van Andel *et al.*, 1975; Shipboard Scientific Party, 2001]. While paleoenvironmental proxies provide an ever-improving record of the pattern of early Cenozoic climatic change, there is still relatively little known about the processes underlying these changes and large uncertainties exist in the interpretation of data.

[3] A widely accepted hypothesis to explain this shift to an Icehouse climate state involves the separation of Antarctica from Australia and the subsequent deepening of the "Tasmanian Gateway" (TG) between the two continents, leading eventually to "thermal isolation" of Antarctica [e.g., Kennett, 1977; Murphy and Kennett, 1986; Exon *et al.*, 2001, 2002]. The most current version of this scenario as presented by Exon *et al.* [2001] is that the tropically derived, warm currents (mainly the Eastern Australian Current or EAC) maintained Eocene high-latitude warmth. In this scenario, the EAC was deflected northward by the onset of a proto-Antarctic Circumpolar Current (proto-ACC), i.e., by an influx of relatively cool surface waters through the Australo-Antarctic Gulf (AAG) into the southwest Pacific, near the end of the Eocene. Originally, this hypothesis was motivated by sparsely distributed isotopic temperature proxy records [Shackleton and Kennett, 1975]

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and calcareous plankton biogeographical affinities [Kennett, 1978], that portrayed the South Pacific Ocean during the Eocene as homogenous and warm, and the early Oligocene as cooler and with increased zonation of bioprovinces (see Nelson and Cooke [2001] for a recent review). It has been assumed that the cause of the extreme warmth of ocean temperatures in this region was a subtropically derived current (the EAC) which transported heat into the region. Testing of this “TG hypothesis,” i.e. for the presence of poleward flowing currents along Australia’s eastern boundary during the Eocene, has been forestalled by a lack of high-resolution data in the crucial Tasmanian region. Recent drilling during Ocean Drilling Program (ODP) Leg 189 focused on unraveling the presumably interrelated climatic and tectonic records in the Tasmanian Gateway during the Eocene-Oligocene transition [Exon *et al.*, 2001, 2002].

[4] The TG hypothesis fundamentally rests upon the assumption that the EAC carried warm water to extremely high latitudes, i.e., to the Antarctic Coast during the Eocene, and that the EAC was responsible, via direct advective heat transport, for a substantial part of Antarctic interior warmth. In recent versions of the TG hypothesis, is the premise that the AAG also was warmed somewhat during the Eocene by the inflow of relatively warm Indian Ocean water [Exon *et al.*, 2001, 2002; McGowran *et al.*, 1997]. These Eocene ocean dynamics are presumed to have substantially altered when TG deepening causing the earliest Oligocene climate change on Antarctica, specifically via continental cooling. A direct prediction of the TG hypothesis is that Eocene planktonic assemblages from both (Indo-Atlantic and Pacific) sides of the Tasman Rise should reflect these subtropical currents in their dispersal patterns and consequently have strong, shared biogeographical affinities with warm water assemblages known from the Tethyan and Indo-Atlantic realms. We test this prediction, and thereby the TG hypothesis itself, by (1) reconstructing the biogeographical distribution of phytoplankton (mainly diatoms and dinoflagellate cysts) using data produced from ODP Leg 189 combined with existing biogeographical data, and (2) numerical model experiments. During this critical interval in Earth’s climatic history, carbonate sediments (including well-preserved calcareous microfossils) are largely absent in this region. Therefore we capitalize on microfossil groups that were underutilized in previous reconstructions, organic-walled dinoflagellate cysts (or “dinocysts”), and diatoms, to provide a new and crucial perspective on the environment of this region, testing the TG hypothesis.

[5] This paper is organized as follows: In section 2, we describe materials and methods used in the collection and analysis of the data and the model configuration used to investigate Eocene climate. In section 3, we present results which demonstrate that, contrary to the results of previous work, TG deepening did not occur synchronously with initiation of Antarctic glaciation, the EAC did not penetrate to high latitudes, and ocean heat transport to high latitudes was not greater than modern. In section 4, we discuss our results in the context of previous work and show that while our interpretations of previous model and data may differ from previous studies, the data themselves do not conflict with our interpretations. In section 5, we evaluate the

conclusions of this work and its implications for the Cenozoic deterioration of climate and the importance of changes in ocean heat transport in that pattern.

2. Material and Methods

[6] ODP Leg 189 recovered earliest Oligocene and older sediments from four drill sites (1168, 1170, 1171, 1172) around the Tasman Rise (~65–70°S paleolatitude), which effectively blocked the eastern end of the widening AAG until ~35.5 Ma [Stickley *et al.*, 2004a] (Figure 1). The recovered sedimentary sequences are entirely marine, with major terrestrial input through the Eocene, and contain rich siliceous and organic microfossil assemblages that record environmental conditions from the latest Cretaceous (~70 Ma) to the early Oligocene. In the Eocene, prodeltaic clays and silts were deposited in water depths increasing from ~50 meters to ~300 meters as Australia and the Tasman Rise separated from Antarctica, and the region subsided gradually. This phase was followed by a shift to deep marine carbonates in the earliest Oligocene as the region rapidly subsided to water depths in excess of 1000 m and was effectively cut off from terrestrial sediment sources [Exon *et al.*, 2001]. As described in the work of Stickley *et al.* [2004a], we reconstruct TG deepening to significant depth actually occurred ~2 Myr before significant Antarctic glaciation (O1).

2.1. Paleogene Dinocyst/Diatom Distribution Patterns From Leg 189 Sites

[7] A record of samples, sample-spacing, analytical techniques, methodologies, and principal results of the quantitative dinocyst and diatom analyses of the Paleogene intervals of the various ODP Leg 189 cores is presented in the various ODP Leg 189 Initial and Scientific Report papers (notably, Brinkhuis *et al.* [2003a, 2003b], Shuijs *et al.* [2003], and Stickley *et al.* [2004b]). Broadly, records of the dinocyst and diatoms can be summarized in terms of species either belonging to (1) a typical high-latitude assemblage of endemic Antarctic (cf. the “trans-Antarctic flora” of Wrenn and Beckman [1982] for dinocysts) and/or “bipolar” affinity, or (2) to a “cosmopolitan” or “Tethyan” assemblage characteristic of middle to low latitudes and associated with warm environs during the Eocene. Listings of the recognized dinocyst and diatom taxa, and their paleobiogeographic affinity, from the various ODP 189 studies may be found in the work of Brinkhuis *et al.* [2003a, 2003b], Shuijs *et al.* [2003], and Stickley *et al.* [2004a]. For the middle to late Eocene interval, the cumulative results are summarized in terms of relative abundance in Figure 1 for all ODP 189 sites, based on the data presented in ODP 189 publications (shown in supplemental Table 1).¹

[8] We note that by “lumping” together broad swaths of time we miss some shorter-termed transient paleoenvironmental excursions. In related studies on specific intervals,

¹Auxiliary material is available at <ftp://ftp.agu.org/apend/pa/2004PA001014>.

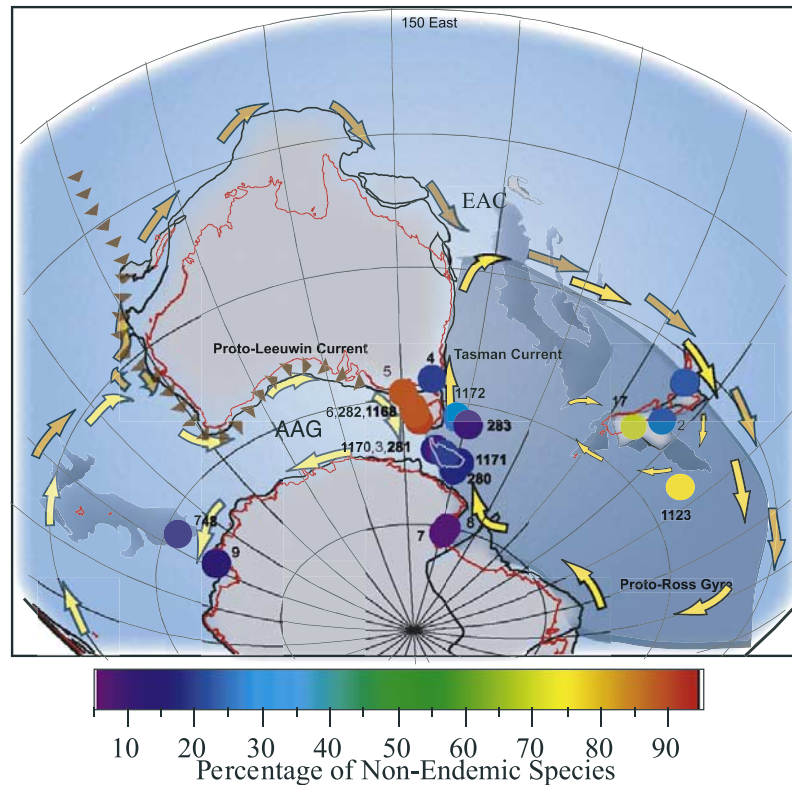


Figure 1. Middle Eocene biogeography and oceanic circulation, Tasmanian region. Biogeographical data collected from ODP Leg 189 and from studies cited here and in supplemental material, as well as a schematic representation of a current distribution consistent with this pattern. The continental positions are reconstructed on a polar stereographic projection for ~45 Ma assuming a fixed Antarctic reference frame (modified from Ocean Drilling Stratigraphic Network Web site (www.odsn.de)). The colored circles indicate percentage nonendemic (e.g., cosmopolitan or Tethyan) taxa. The values were calculated by averaging together percentages of nonendemic diatoms and dinocysts taken from the middle and late Eocene (see supplemental material). Sites labeled with boldface are ODP and DSDP site numbers; otherwise the numbers refer to localities described in the supplemental material. Sites along the northern margin of the AAG are dominated by nonendemics, whereas sites on the Pacific side, as well as along the Antarctic margin, are almost entirely endemic. The brown triangles represent the path of dispersal of brachiopods as well as other taxa with tropical affinities, as summarized in the work of *Craig* [2002] and *McGowran et al.* [1997]. The dark shaded zone in the southwest Pacific indicates the Weddellian zone of *Zinsmeister* [1979]. The brown and yellow arrows indicate the paths of the subtropical and subpolar gyres, respectively. In general, our reconstruction predicts that the majority of Paleogene (sub)tropical Southern Hemisphere taxa dispersed east and poleward, especially along eastern coastal boundaries, whereas endemic Antarctic taxa dispersed westward and equatorward along western coastal boundaries. Oceanic current names are indicated on the chart. Lord Howe Rise and Kerguelen Plateau are indicated with shading.

notably from Site 1172, by using a similar approach, we are able to recognize such transient events (e.g., the middle Eocene Climatic Optimum of *Bohaty and Zachos* [2003] in great detail [e.g., *Brinkhuis et al.*, 2003c; *Röhl et al.*, 2004]). The lumped approach taken here we consider useful and necessary because it highlights the major patterns that hold true in general for the middle and late Eocene. As most of the deep ocean temperature records agree, the majority of cooling between the warm early Eocene and the cooler early Oligocene actually occurred by the middle Eocene, and temperatures were relatively stable through the late middle, and late Eocene, consequently we believe that these broad averages are representative.

2.2. Additional Biogeographical Phytoplankton Data

[9] We have complemented the Leg 189 Eocene diatom and dinocyst distribution analysis by compiling literature biogeographic information of these groups from the circum Antarctic region. A summary of results is presented in supplementary material Table 1. In addition, we compiled existing calcareous nannoplankton information, presented in supplementary material Table 2. These results are integrated into our discussion in sections 3 and 4.

2.3. CCSM Model and Simulations

[10] We have used the National Center for Atmospheric Research's Community Climate System Model (CCSM)

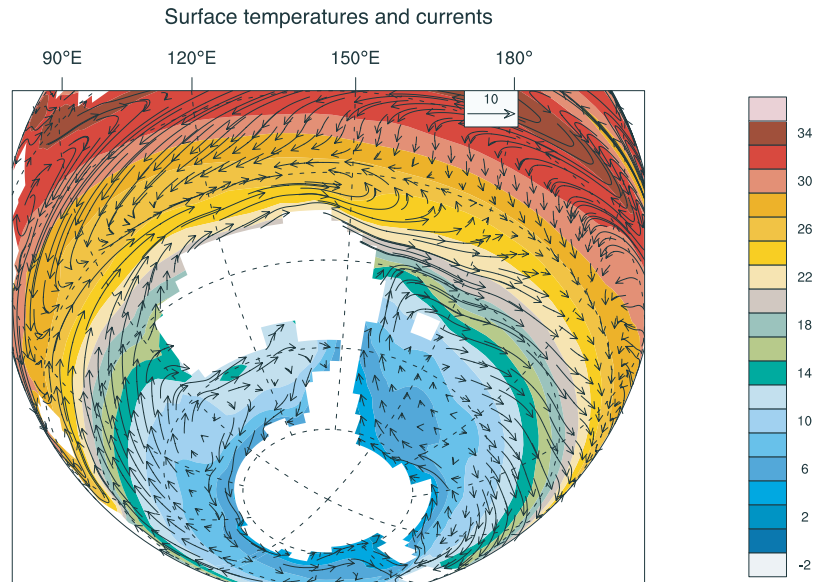


Figure 2. Model sea surface temperature and velocity results. Mean annual surface temperature and currents as produced by a fully coupled general circulation model, including temperatures (in °C) and vector magnitudes (in cm s^{-1}). The presence of two subpolar gyres is evident. Associated with these gyres are the proto-Leeuwin current, bringing relatively warm water into the AAG, and the Tasman Current, advecting water north from the Antarctic coast. As shown in Figure 3, these currents are wind-driven and are hence not sensitive to ocean model details, nor to variations in model spin-up techniques, initial conditions, or greenhouse gas concentrations. Sea surface and deep ocean temperatures are sensitive to changes in greenhouse gas concentrations [Huber and Caballero, 2003] (Table 1). Note the broad region of relatively homogenous temperatures in the southwest Pacific, which is evocative of the lack of thermal fronts noted previously from studies [Kennett, 1978; Murphy and Kennett, 1986; Nelson and Cooke, 2001]. There is some variability associated with the seasonal cycle and with the presence of Antarctic deep convection, which is responsible for importing small amounts of warmer, saltier water poleward and to the east of New Zealand.

version 1.4, in its paleoconfiguration: 18 vertical levels and T31 spectral resolution ($\sim 3.75^\circ \times 3.75^\circ$) in the atmosphere and land surface; the ocean and sea ice models use a stretched horizontal grid (tropics: $\sim 9^\circ$ latitude by 3.6° longitude; extratropics: 1.8° latitude spacing), with the ocean utilizing a stretched vertical coordinate and 25 levels. CCSM has been shown to produce stable quasi-steady state climates for modern [Boville and Gent, 1998; Boville et al., 2001; Blackmon et al., 2001; Otto-Bliesner and Brady, 2001], Last Glacial Maximum [Shin et al., 2003], early Paleogene [Huber and Sloan, 2001; Huber et al., 2003], and Cretaceous [Otto-Bliesner et al., 2002] conditions. Here we focus on one Eocene simulation (“Eocene A”) described further in the work of Huber and Caballero [2003], in which we used anisotropic ocean viscosity, a realistically small background ocean diffusivity coefficient ($f_{kph} = 0.15 \text{ cm}^2 \text{ s}^{-1}$), and a $p\text{CO}_2$ concentration of 560 ppm. The boundary conditions and spin-up technique have been fully described elsewhere [e.g., Huber and Sloan, 2001; Huber et al., 2003]. In short, Eocene A (in Figure 2) has undergone 3 separate 55-year fully coupled iterations interspersed with 3 uncoupled, accelerated ocean integrations, totaling 3160 years of spin-up, after

which the simulation has negligible temperature and salinity trends. After spin-up, a further 370 fully coupled years were simulated (all results reported here refer to the last 240 years). In Eocene A: we find that deep convection occurs in the Southern Hemisphere, with sinking occurring preferentially between the southeast of New Zealand and Antarctica (near the modern Amundsen Sea). To test the robustness of our results, we compared against a suite of model runs employing a different ocean viscosity parameterization (“Eocene B”) which was integrated for over 9000 (accelerated) years, other spin-up procedures (“Eocene C”), and higher $p\text{CO}_2$ (1120 ppm in “Eocene D”). Circulation patterns in these simulations were extremely similar to each other, so we focus on one, Eocene A. We chose Eocene A as our reference case because sinking occurs in the Southern Pacific Ocean thus this case is likely to maximize transport of warm water into high latitudes, allowing us to make the closest and most fair comparison of our modeling results to the TG hypothesis. We used three modern cases as controls to compare ocean heat transport with: these cases are “NCAR CCSM,” a standard run carried out by NCAR; “Preindustrial A,” an extension of the “degraded” simulation described in the work of Huber and Sloan [2001]

Table 1. Sea Surface Temperatures^a

	Proxy Estimates	Modeled, 560 ppm	Modeled, 1120 ppm
Location of DSDP Site 277	11.5–14.5 (9.5–12)	10	12
Location of DSDP Site 592	(10–11)	13	14
Location of DSDP Site 593	(10–13)	11	12
New Zealand brachiopods, mixed foraminifera	(11–13), (12–16)	12	13

^aThis summarizes a variety of late middle to late Eocene SST estimates from proxies and models (units are °C). Proxy records are grouped into two groups, late middle to latest middle Eocene and late Eocene; the latter is denoted by parentheses. In the right two columns are collocated mean annual SSTs produced by the model for two different greenhouse gas concentrations as indicated in the table. These are results from Eocene A and Eocene D. The DSDP site estimates are taken from *Feary et al.* [1991] and *Buening et al.* [1998] and are based originally on the work of *Shackleton and Kennett* [1975] and *Murphy and Kennett* [1986]. These data are comparable to those in the work of *Zachos et al.* [1994]. The New Zealand data are taken from *Buening et al.* [1998], which includes estimates based on brachiopod isotopes records performed by those authors, as well as mixed planktonic foraminiferal oxygen isotopic records produced by *Burns and Nelson* [1981].

including albedo degradation; and “Preindustrial B” which is similar to Preindustrial A, but with albedo degradation turned off.

3. Results

3.1. Phytoplankton Compilations

[11] The Eocene dinocyst assemblages at Site 1168 (in the AAG, the westernmost site) are comparable to those known from subtropical and tropical (we refer to as Tethyan) waters [*Brinkhuis et al.*, 2003a]. We thus interpret this assemblage as a signal of relatively warm water, either as a local warm-water assemblage, or as sampling a water mass that is derived from a warm-water source [*Brinkhuis et al.*, 2003a] (see Figure 1). Conspicuously, species endemic to Antarctica are virtually absent at this locality. This stands in stark contrast to Sites 1170, 1171 and 1172 where Eocene dinocyst assemblages are predominantly composed of Antarctic endemic species (comparable to those reported by, e.g., *Wrenn and Beckman* [1982], *Wrenn and Hart* [1988], and *Truswell* [1997]). Bipolar species are common, while long-ranging cosmopolitan and Tethyan taxa are infrequent [*Brinkhuis et al.*, 2003b; *Sluijs et al.*, 2003; *Stickley et al.*, 2004a].

[12] Diatom assemblages are conspicuously absent from the coeval interval at Site 1168, but abundant, well-preserved and diverse diatom assemblages occur consistently from the middle Eocene and throughout the Oligocene intervals at Sites 1170, 1171 and 1172 [*Sluijs et al.*, 2003; *Stickley et al.*, 2004a]. Eocene diatom floras at these sites are composed predominantly of abundant, robust, shallow-water planktonic and benthic-neritic marine taxa. This assemblage, identified as a flora endemic to the greater Ross Sea region, includes many undescribed species [*Stickley et al.*, 2004a]. Within this assemblage, there are a small number of offshore long-ranging cosmopolitan taxa.

[13] Although Eocene paleodepths and depositional settings are quite comparable among the Leg 189 sites, major differences in relevant phytoplankton assemblages are immediately apparent: (1) Site 1168 is characterized by Eocene dinocyst assemblages that are comparable to those known from relatively warm, tropical to subtropical, Tethyan waters and which contain virtually no endemic Antarctic dinocysts. Diatoms are altogether absent. (2) The Eocene successions at Sites 1170–1171–1172 are characterized by assemblages of dinocysts and diatoms where the predominant species (on average ~90% of the assemblage) can be described as endemic or bipolar (dinocysts only),

with rare cosmopolitans and tropical-subtropical species virtually absent.

[14] The ODP 189 data are supplemented here with published diatom and dinocyst distributions from the entire region (see supplementary material Table 1). The resulting biogeographical patterns expand and reinforce our ODP Leg 189-based findings (Figure 1). These results clearly indicate that AAG surface waters were markedly different from those in the southwest Pacific, consistent with the existence of a barrier to transport between the AAG and the Ross Sea region during the Eocene. More to the point, given the high degree of endemism, the water mass in the greater Ross Sea region was not subtropical, i.e., it was not derived from low-latitude Pacific waters via the EAC, but rather reflected sources from the Antarctic region itself.

[15] The sparsely distributed, depauperate and poorly diversified calcareous microplankton assemblage in the Eocene ODP 189 materials are regarded as “largely cosmopolitan” [*Shipboard Scientific Party*, 2001]. In contrast to the diatoms and dinocysts, the Southern Hemisphere calcareous nannoplankton distribution apparently lacks ubiquitous endemic Antarctic taxa, although broadly, an affinity with Southern Indian, Atlantic or Pacific assemblages is apparent (see supplementary material Table 2). This may be considered consistent with the biogeographic analysis of *Wei and Wise* [1990a, 1990b] who showed that strong meridional biogeographic gradients were established in the South Atlantic at least as early as the middle Eocene.

3.2. CCSM Model Experiments

[16] To better understand the regional Southern Ocean circulation and investigate the implications of the emerging biogeographical patterns, we compared them to results from fully coupled Eocene climate model simulations. As described above, we have explored a range of plausible pre-TG opening Eocene boundary conditions with NCAR’s CCSM and found robust ocean current results and produced climate in agreement with the Southern Pacific Ocean oxygen isotopic surface (see Table 1) and deep ocean temperature proxies [e.g., *Huber and Caballero*, 2003].

[17] In the simulations, clockwise subpolar gyres dominate the Southern Ocean circulation (Figure 2), as they do in all the high-latitude oceans (Figure 3). The clockwise “Proto-Ross Gyre” produces a relatively cool, northward flowing current along the eastern margin of Australia, that we here term the Tasman Current, which is analogous to the modern Oyashio and Falkland currents. This current cools

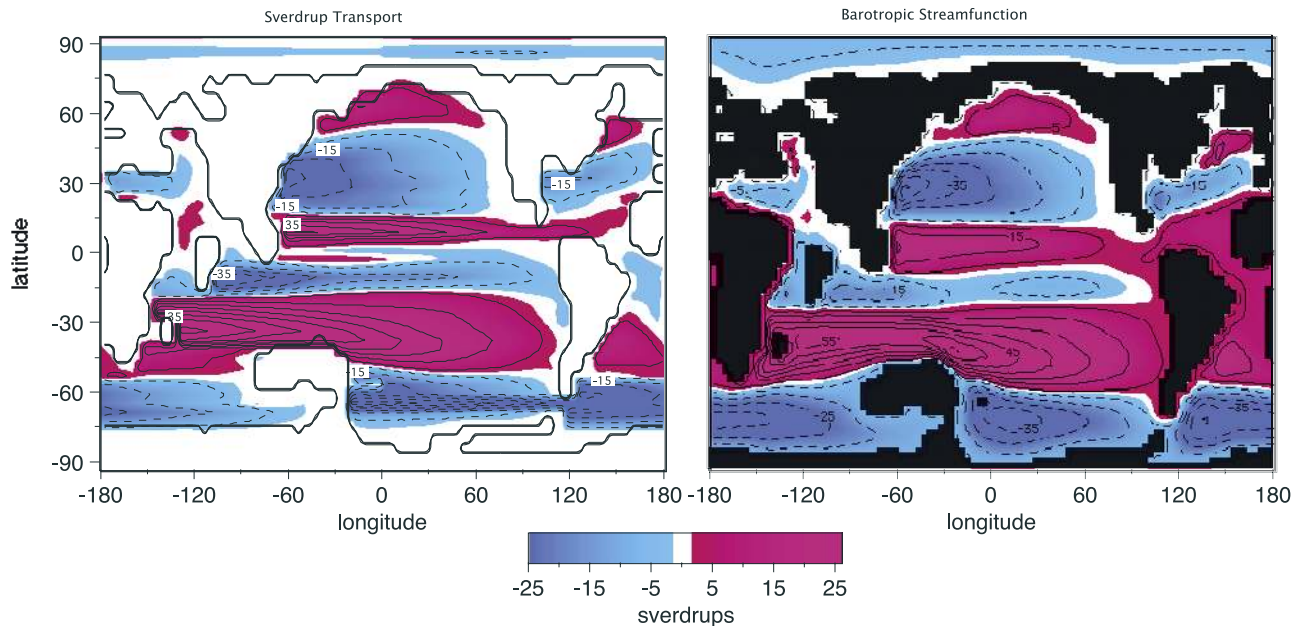


Figure 3. Comparison of Sverdrup transport and barotropic stream function. On the left is shown the estimate wind-driven ocean gyre transport in equilibrium with the AGCM-derived winds by calculating the Sverdrup transport driven by the wind stress curl (that is the geostrophic response to the Ekman pumping velocities). The methods are fully described in the work of *Huber* [2001]. Theory suggests to first order that the vertically integrated velocities (barotropic) should correspond closely to the Sverdrup transport, which is confirmed by the comparison to the barotropic stream function produced by the ocean model on the right. Clockwise gyres are indicated in blue, counterclockwise gyres in red. The flow is contoured at 10 Sverdrup intervals. The correspondence between the upper ocean velocities shown in Figure 2, the Sverdrup transport driven solely by the wind fields, and the barotropic streamfunction produced by the full ocean general circulation model of CCSM, clearly demonstrate that the major current system discussed here (the EAC and Tasman currents) are wind driven and parts of the subtropical and subpolar gyres respectively.

($\sim 25 \text{ W/m}^2$ convergence) the atmosphere, rather than warming it, as required by the TG hypothesis. The EAC exists in the simulation (Figure 2), but its poleward travels are limited to Australia's northern margin, whereupon it deflects eastward (this feature is analogous to the modern Malvinas-Brazil Confluence). Extensive sensitivity studies and analysis of the wind-driven component of the circulation (Figure 3) demonstrate that the Tasman Current and Proto-Ross Gyre are primarily wind-driven (i.e., Sverdrupian) and therefore are neither sensitive to ocean modeling details nor to a plausible range of Paleogene sea surface temperatures or greenhouse gas concentrations [Huber, 2001]. The latitude of the separation of the EAC from the coast is primarily determined by the wind stress curl, and the presence of a northward flowing Tasman Current is a direct product of the zonally integrated wind stress curl (Figure 3). These results are in agreement with the independent simulations by *Omta and Dijkstra* [2003]. On the Gulf side of Tasman Rise, a Proto-Leeuwin Current transports relatively warm, salty water, including a subtropical Indian Ocean-derived component, into the AAG.

[18] We propose that the clockwise gyre dispersed taxa (Figures 1 and 2) poleward before bringing them near the Pacific side of Tasman Rise, and therefore the potential existed near the Antarctic coast for a “cold trap” that

filtered out cold-intolerant taxa. During periods of peak Eocene warmth, when the Antarctic coast was warmer than a threshold value, cold intolerant Tethyan-derived taxa propagated along the clockwise circuit into the south west corner of the Pacific. During periods with a greater temperature gradient (e.g., the middle and late Eocene) these taxa may have been filtered out in the cold trap. The episodic incursions of cold-intolerant taxa in the proxy record in the south west Pacific may consequently be explained as reflecting changes in temperatures off the coast of Antarctica rather than changes in current directions.

[19] To define the water mass history produced in the simulation and compare objectively to the biogeographic data presented in Figure 1, we use Lagrangian back trajectory analysis. The numerical techniques used here have been extensively validated in the modern ocean *Döös* [1995] and shown to accurately predict water mass paths around Tasmania [Speich et al., 2002] and planktonic larval dispersal [Kimura et al., 1999]. To predict biogeographic provinces from the climate model output, we make the rudimentary approximation that the percentage of taxa with Tethyan affinities in a site depends on the fraction of water at a given site that has not been filtered through the cold trap (i.e., experienced temperatures strictly $>4^\circ\text{C}$), or in other words, on the percentage of water that has taken the “warm water

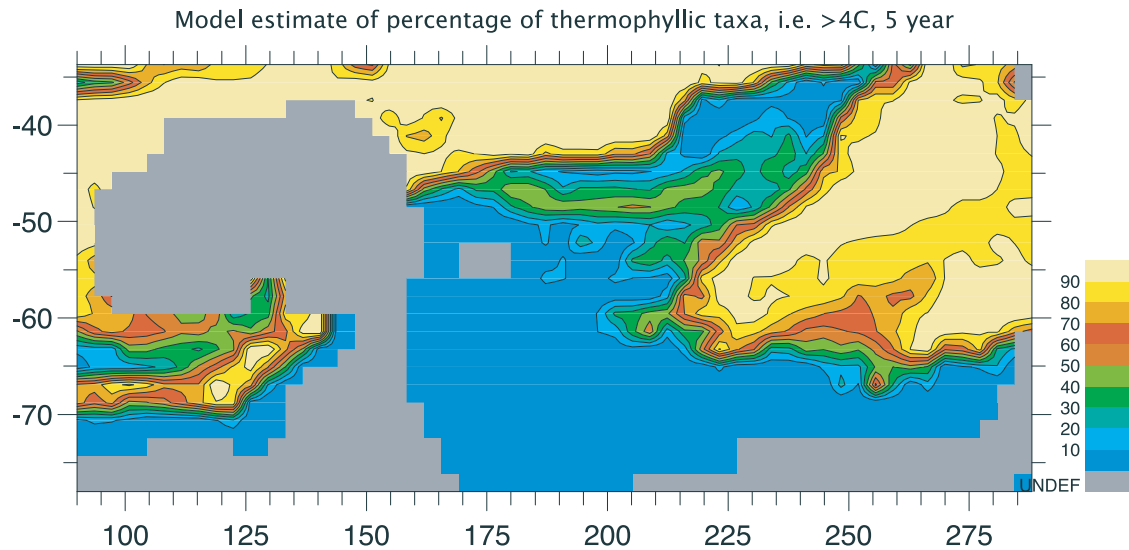


Figure 4. Model-predicted biogeographic affinities. A biogeographic affinity map derived using a method described in the text, to be compared with the proxies shown in Figure 1. The colorbar indicates the percentage of “Tethyan,” i.e., cold-intolerant taxa expected from the model.

path” to a given site. Lagrangian back trajectories are used to calculate the percentage of volume transport that experiences temperatures along its path at no point less than 5°C (within a five year timescale). By assuming that there is a linear relationship between the percentage of warm water taxa within the assemblage at a given locale and percentage of ocean transport into that region via the “warm water path” as calculated from the simulation, we construct a biogeographic affinity map (Figure 4) commensurate with the proxies shown in Figure 1.

[20] While crude, these analyses generally reproduce the biogeographic pattern evidenced by the biotic proxies discussed above: The EAC heads eastward from the Australian coast as a jet that manifests itself as a strongly “endemic” zone displaced equatorward (Figure 4), which is consistent with the existence of strongly endemic assemblages near New Zealand (Figure 1). The general pattern of a greater connection to the warm water path in the more central-eastern Pacific shown in Figure 4 is identifiable in the proxies (Figure 1) and may partially explain previous interpretations of a southward flowing EAC [e.g., Kennett, 1978].

[21] By itself, establishing that there was no poleward penetrating, warm EAC does not preclude the existence of increased ocean heat transport in the Eocene, a strong equatorward, cool current can be just as important in this regard. As shown in Figure 5, however, none of the fully coupled Eocene cases produced significantly greater than modern ocean heat transport poleward of 60°S , and certainly none come close to providing the order of magnitude heat transport increase necessary to explain small Eocene thermal gradients (Figure 5).

4. Discussion

[22] The modeling results match, both qualitatively and quantitatively, our biogeographical reconstructions and ex-

plain the apparently divergent biogeographical patterns on both sides of the TG. Moreover, the proposed current systems clarify the otherwise enigmatic evidence of subtropical climate from terrestrial floral and coastal isotopic proxies in the AAG [Greenwood and Wing, 1995; Buening et al., 1998; Kamp et al., 1990] recorded at the same time as New Zealand and Pacific ODP sites indicate sea surface temperatures $\sim 8^{\circ}\text{C}$ cooler [Buening et al., 1998]. They also provide a mechanism for the presence at Cascade Seamount (located on East Tasman Rise) of a temperate to cool-temperate foraminiferal assemblage with much stronger affinities to New Zealand (thousands of kilometers away) than to the nearby South Australia Coast as noted by Quilty [2001]. These currents may also elucidate the problematic distribution of Cretaceous/early Paleogene Southern Ocean brachiopods [Craig, 2002], and larger foraminifera, echinoids, and other organisms of apparently low-latitude or Tethyan affiliation [McGowran et al., 1997] that appear to have spread slowly southward (into the AAG) during the Eocene, with their eastward progress halted until after the Eocene-Oligocene boundary, when many of these taxa first appear on the Pacific side of the TG. Furthermore, polar, endemic Southern Ocean assemblages, consistent with our proposed barriers to transport, have long been recognized in disparate lineages, albeit by various names, e.g., the “Weddelian molluscan fauna” [Zinsmeister, 1979].

[23] As a further dynamical check on these predictions, the existence of subpolar gyres in the Southern Ocean is consistent with the same sense of rotation and similar endemism interpreted from other proxy records both in the North Pacific [Oleinik, 2001] and in the South Atlantic [Wei and Wise, 1990a; Barker et al., 1999]. Thus, although sufficient data to confirm the nature of the regional circulation in the Tasman Rise region did not exist before Leg 189, our reconstructed circulations broadly match many, thus far, poorly understood paleocirculation and paleoenvironmental proxies and are consistent with some earlier,

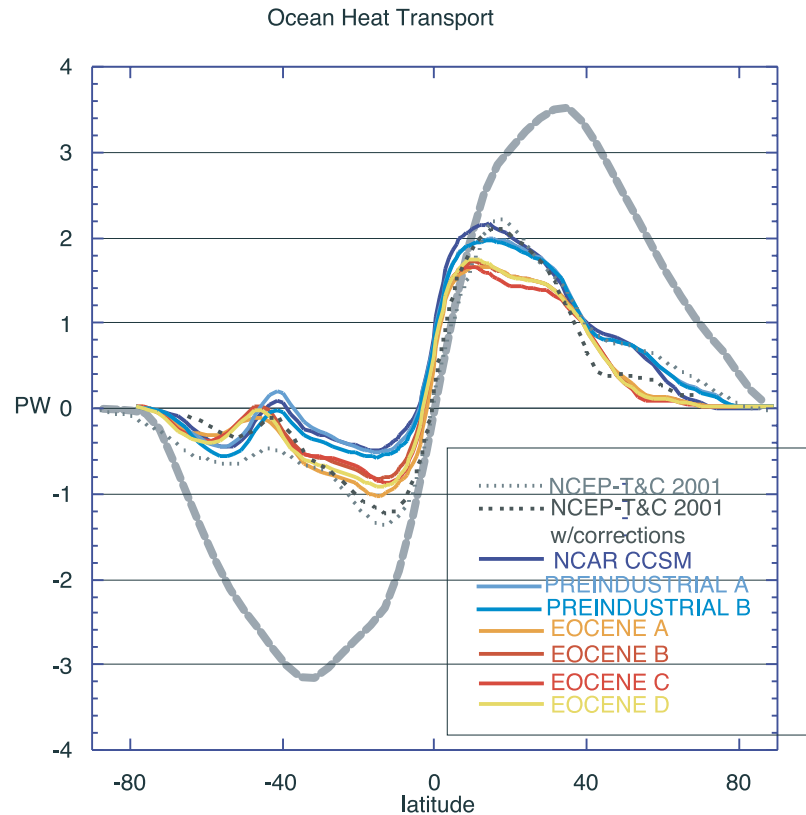


Figure 5. Ocean heat transport from a variety of sources is shown. The two dotted lines indicate modern ocean heat transport as estimated by *Trenberth and Caron* [2001]. The black dotted line represents a state where ocean heat transport beyond 65° latitude is exactly zero, whereas the gray dotted line incorporates nonzero high-latitude surface heat convergence. Taken together, they provide estimations of modern ocean heat transport, a poorly known quantity in the modern Southern Ocean. The blue lines indicate ocean heat transport as predicted by a fully coupled model for three experiments with preindustrial boundary conditions (described in text). These three cases produce nearly identical heat transport estimates, which are well within the observed range for modern day. Four Eocene cases are also shown: Eocene A is the case shown in Figure 2, and the other cases are described in the text. Heat transport within the subtropics is about 0.6 PW more in the Eocene cases than the modern case in the Southern Hemisphere, and the opposite situation occurs in the Northern Hemisphere. This pattern is consistent with the predicted response for having closed Southern Ocean gateways [*Toggweiler and Bjornsson*, 2000]. Nevertheless, both modern and Eocene heat transport values are within the wide uncertainties for the modern day. Critically, for the issue of Antarctic glaciation, at high latitudes the result of the simulations are indistinguishable. The minimum ocean heat transport required in order to have maintained polar warmth is indicated by the thick gray line [*Huber et al.*, 2003]. All of the simulations fall far short of this mark.

more intuitive efforts [*Haq*, 1981; *Lazarus and Caulet*, 1993].

[24] The conclusions reached here appear at odds with previous interpretations of the Eocene circulation in the southwest of the Pacific Ocean [*Exon et al.*, 2002; *Nelson and Cooke*, 2001]. Most previous reconstructions are based on the presence of “cosmopolitan” biota in open ocean sediments in the midlatitude Southwest Pacific, the presence of calcareous versus siliceous sediments in the high-latitude deep ocean (summarized in the work of *Nelson and Cooke* [2001]), and by oxygen isotopic analysis performed on some of these taxa [*Shackleton and Kennett*, 1975]. The rare Eocene nannoplankton assemblages found in Leg 189 bear a resemblance to those found in the South Atlantic

during this interval (supplementary Table 2), which *Wei and Wise* [1990a, 1990b] have demonstrated are biogeographically distinct from low-latitude Atlantic assemblages. Thus, far from indicating the lack of barriers to transport, these assemblages may indicate the pervasiveness of biogeographic barriers in high-latitude oceans, as noted by *Wei and Wise* [1990b]. The interpretation of calcareous deposition as indicating warm conditions (and siliceous indicating cold) does not prove any causal link between ocean currents and climate [*Barker and Thomas*, 2004]. The isotopic reconstructions may be evidence for small temperature gradients within the region that they sample. It is a matter of practical importance that, in order to invert a tracer field to infer a circulation, the gradient in the tracer should be

strong (and ideally there should be multiple tracers), any conceivable flow field is compatible with a uniform tracer distribution. Therefore these proxies provide little constraint on the ocean circulation in this time interval, they could be compatible with a poleward penetrating EAC, or a northward flowing Tasman Current. When an array of tracers is considered, it is the tracers that show gradients that provide the most constraints on flow direction. As a consequence, we view the presence of strong gradients (Tethyan versus Endemic) in diatom and dinocyst assemblages as providing more useful current direction information than the relatively gradient-free nannoplankton records. Furthermore, if waters cooled little as they flowed south (as required by the TG hypothesis) then no significant heat could have been lost to the atmosphere [Sloan *et al.*, 1995], and consequently warming would not be felt on land, thus being inconsistent with the rationale of the TG hypothesis. Consequently, the environmental pattern used to infer a paleocirculation in these earlier studies does not actually provide useful information for that estimation, and to the degree that the inferred circulation is reasonable it implies little heat transport by the EAC, which makes the TG hypothesis untenable. Our results (Figure 2; Table 1) clearly show relatively small north-south temperature gradients in the Southwest Pacific without maintaining a poleward penetrating EAC. Instead, heating of the ocean is provided by the atmosphere, as it is in this region today.

[25] Many studies have been published that appear, however, to support or at least invoke the circulation proposed by Kennett [1978] and as modified by Murphy and Kennett [1986] and Exon *et al.* [2001, 2002]. We have conducted a literature review to determine if there are independent records that tend to support this circulation reconstruction. Interestingly, there are many proxy-based studies that contain information on paleotemperatures, salinities, upwelling, and other important environmental parameters, that also show maps of the inferred paleocirculation [Diester-Haass and Zahn, 2001; Gammon *et al.*, 2003; Buening *et al.*, 1998], which in general are identical to those of Murphy and Kennett [1986] or the circulation of Kennett *et al.* [1975]. Upon closer inspection it is apparent, however, that the maps are in fact credited directly to Murphy and Kennett [1986] or Kamp *et al.* [1990] (which in turn cites Murphy and Kennett [1986]). In the papers listed above, in which explicit paleocirculations are depicted, we have examined the published proxy records described and find, that in general, these studies are more consistent with the circulation one proposed here, or they provide little independent direct constraint on the paleocirculation.

[26] On physical grounds, the circulation proposed here is more defensible. Indeed, without fundamental reorganization of the high and low pressure systems (switching them), in the Southern Hemisphere, the wind patterns that drive these circulations are inevitable [Huber, 2001; M. Huber and D. Nof, The oceanic circulation in the Southern Hemisphere and its climatic impacts in the Eocene, submitted to *Global and Planetary Change*, 2004]. This robustness of the wind driving is the reason that ocean circulation models produce a northward flowing and vigorous Tasman Current (Figure 3; see also Omta and Dijkstra [2003]) for

Paleogene conditions. This, by itself, does not preclude that ocean heat transport may have been higher during the Eocene, but it does indicate that Pacific ocean heat transport changes would have been more sensitive to gateway opening along the Pacific's eastern boundary, i.e., Drake Passage [Lawver and Gahagan, 1998] rather than its western boundary.

[27] The fact that the fully coupled GCM we use in these experiments does not produce high-latitude ocean heat transport (e.g., past 60°S, Figure 5) significantly larger than modern is consistent with the independent studies of Najjar *et al.* [2002] and Sijp and England [2004]. Our simulations do produce the increase of heat transport into the Southern Hemisphere predicted by Toggweiler and Bjornsson [2000] with a closed Southern Ocean gateway (~0.6 PW), but importantly the increase is largely limited to the subtropical ocean heat transport maximum, there is no significant heat transport change across 60°S. These results indicate that changes in Southern Ocean gateways and heat transport may have led to subtropical sea surface temperature changes of ~2°, but did not directly play a leading role in high-latitude climate change. Nevertheless, it is important to point out that the two results, (1) direction of the flow in the Southern Pacific and (2) Southern Ocean heat transport and surface ocean temperature change, are separate, and subject to different uncertainties. The first result is a robust consequence of the general circulation of the atmosphere and ocean and is confirmed by data. The second result is more likely to be sensitive to modeling details and especially the sensitivity of the surface climate to forcing, e.g., its CO₂ doubling sensitivity, sea ice model formulation, and diapycnal mixing treatment. Models have produced a range of likely sea surface temperature changes (1–3°C) due to the small changes in ocean heat transport produced [Mikolajewicz *et al.*, 1993; Toggweiler and Bjornsson, 2000; Najjar *et al.*, 2002].

5. Concluding Remarks

[28] A central tenet of paleoceanography is that the opening and closing of ocean gateways has led to significant changes in poleward heat transport by the ocean, thereby dramatically altering climate (J. P. Kennett, personal communication, 2003). The apparent synchronicity of the initiation of widespread glaciation and the opening of the TG near the Eocene-Oligocene boundary, and the interpretation of a poleward penetrating, warm EAC have been key pieces of evidence for this mechanism.

[29] Our reconstructions indicate that Antarctica's shores on the Pacific side of Tasman Rise were not kept warm by southward flowing subtropical water masses during the Eocene, but instead were cooled by an equatorward flowing Tasman Current. Furthermore, in a companion paper, we find [Stickley *et al.*, 2004a] that TG opening preceded significant glaciation by ~2 Myr. These results demonstrate that whatever was responsible for the initiation of substantial Antarctic glaciation at the beginning of the Oligocene, it was not the direct dynamical effect of terminating a southward flowing EAC. Indeed, if we can conjecture anything, deepening of the TG should have allowed the warm, wind-

driven proto-Leeuwin current to penetrate into the Southern Pacific Ocean, thus causing a causing a mild warming of the region, not a cooling.

[30] Nor, if the model results are correct, was glaciation on continental Antarctica likely to have been an effect of heat transport changes driven by other current systems. Our fully coupled simulations reveal near-modern levels of ocean heat transport in the high-latitude Southern Ocean (Figure. 5). *DeConto and Pollard* [2003] have demonstrated that changes in ocean heat transport, even if they did occur, are unlikely to have induced Antarctic glaciation; this provides an important complement to our study. These results argue for a reexamination of the central role in paleoceanography played by changes in ocean heat transport due to gateway changes.

[31] Considering that (1) Antarctica was not kept warm by subtropical currents, (2) evidence of above-freezing Eocene continental interior winter temperatures occurs in high latitudes of both hemispheres, and (3) substantial carbon cycle changes coincide with the Eocene-Oligocene boundary, the most parsimonious explanation of the enigmatic global warmth of Eocene climate was that it was caused by atmospheric mechanisms, such as greenhouse gas radiative forcing [*Sloan and Rea*, 1996; *Pearson and Palmer*, 2000; *Shellito et al.*, 2003] and potential feedbacks [*Sloan and Pollard*, 1998; *Otto-Bliesner and Upchurch*, 1997]. The implication is that changes in greenhouse gas concentrations and subsequent feedbacks were primarily responsible for climatic deterioration into the Oligocene.

[32] These results do not demonstrate that late Eocene tectonic evolution and opening of Southern Ocean gateways

were unimportant for causing significant Antarctic glaciation. They do, however call into question both the timing that has been invoked to link these events and the causal mechanisms that they involve. It may be necessary to shift focus to a critical, but less-explored result of paleoceanographic investigation, that major changes in the global oceanic carbon reservoir can be driven by ocean gateway changes [*Heinze and Crowley*, 1997], or by changes on coastal margins or elsewhere, driven by the same tectonic processes that drove the separation of Australia from Antarctica. However, it remains to be shown that the approximate coincidence of gateway opening and glaciation was anything more than that, an approximate coincidence. We believe that the fundamental processes that led to Antarctic glaciation, the climatic turning point of the Cenozoic, are complex and remain unknown, and therefore we do not have a firm basis to understand its subsequent evolution and its future behavior.

[33] **Acknowledgments.** This research used samples and data provided by the Ocean Drilling Program (ODP). ODP is sponsored by the U.S. National Science Foundation (NSF) and participating countries under management of Joint Oceanographic Institutions (JOI) Incorporated. Funding for this research was provided by US and international agencies. HB thanks NWO, the Netherlands Organization for Scientific Research; CES thanks the Natural Environment Research Council (NERC)/UK-ODP for support. MH gratefully acknowledges L. C. Sloan for support via NSF ATM 9810799 and the Packard Foundation and thanks the Danish Center for Earth System Science and Purdue University for support during various phases of this project. All computing was performed at NCAR which is supported by NSF. This is NSG contribution 20041201. SAS gratefully acknowledges support from an NSF Earth Sciences Post-Doctoral Research Fellowship and funding from JOI USSSP.

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