Tropical sea temperatures in the high-latitude South Pacific during the Eocene

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ABSTRACT

Sea-surface temperature (SST) estimates of ~30 °C from planktic foraminifera and archaeal membrane lipids in bathyal sediments in the Canterbury Basin, New Zealand, support paleontological evidence for a warm subtropical to tropical climate in the early Eocene high-latitude (55°S) southwest Pacific. Such warm SSTs call into question previous estimates based on oxygen isotopes and present a major challenge to climate modelers. Even under hypergreenhouse conditions (2240 ppm CO_2), modeled summer SSTs for the New Zealand region do not exceed 20 °C.

INTRODUCTION

New approaches to estimating sea temperature from geological archives are revolutionizing our understanding of early Cenozoic climate. Sea-surface temperature (SST) estimates from oxygen isotopes and magnesium/calcium (Mg/Ca) ratios of well-preserved foraminifer tests from shelf sediments are warmer by 10 °C than estimates based on tests of the same species in nearby deep sea cores (Sexton et al., 2006; Zachos et al., 2006; Pearson et al., 2007). The new lipid-based temperature proxy, TEX_{86} (Schouten et al., 2002), is an independent test of SSTs derived from foraminifera and also suggests significantly higher SSTs (Zachos et al., 2006; Pearson et al., 2007). It now seems that much of the planktic foraminiferal SST record in deep sea cores has been contaminated by cool seafloor calcite during early diagenesis (Schrag, 1999). For low latitudes, these new approaches help to reconcile geochemical temperature data with greenhouse climate models (Huber and Sloan, 2001; Shellito et al., 2003) and paleontological evidence (Adams et al., 1990), both of which indicate much warmer SSTs than suggested by the purported surface-water record in deep sea cores. New multiproxy evidence for hypertropical SSTs of >30 °C in the coastal North Atlantic (Zachos et al., 2006) and western central Indian oceans (Pearson et al., 2007) is consistent with the estimated high pCO_2 for the early Eocene, which ranges from 800 to 2500 ppm (Pearson and Palmer, 2000) to >1125 ppm (Lowenstein and Demicco, 2006). For the low-latitude Pacific, surface temperatures of >30 °C have been derived from Mg/Ca ratios (Tripati et al., 2003), but multiproxy data sets or robust high-latitude data have been lacking. This severely limits our understanding of early Cenozoic climate drivers, especially as the Pacific may have been responsible for ~90% of global ocean heat transport during the Paleogene (Huber and Sloan, 2001).

In this study we use TEX_{86}, Mg/Ca, and $\delta^{18}O$ to estimate sea temperature across the termination of the early Eocene climatic optimum (EECO) in outer shelf–upper slope siliciclastic sediments in the Canterbury Basin, New Zealand. At a paleolatitude of ~55°S (Lawver et al., 1992), this record provides an important test of the extent of South Pacific warming under extreme greenhouse conditions. We compare our temperature estimates with existing geochemical and paleontological data for the region and with modeled temperatures from a new coupled ocean-atmosphere general circulation model for hypergreenhouse conditions.

MATERIAL AND METHODS

Rock samples were collected from a 60-m-thick section through Eocene Ashley Mudstone exposed on the middle branch of the Waipara (mid-Waipara) River, North Canterbury (GSA Data Repository Fig. DR1[1]). The age range of the section is based on foraminiferal, calcareous nannofossil, radiolarian, and dinoflagellate cyst (dinocyst) biostratigraphy (Fig. DR2). Depositional conditions were inferred from these fossil assemblages and other palynological and geochemical parameters.

TEX_{86} temperature estimates are based on the relative distribution of archaeal glycerol dialkyl glycerol tetraether (GDGT) marine lipids (Schouten et al., 2002, 2007). Conversion of TEX_{86} values to SST utilizes the revised calibration of Kim et al. (2008), which is linear to 30 °C. The branched to isoprenoidal tetraether (BIT) index is a proxy for soil organic matter input into marine realms (Hopmans et al., 2004). Relatively low BIT values in this section (Fig. 1A) indicate that archaeal GDGTs are primarily marine and that TEX_{86} is not biased by contributions from soil archaea (Weijers et al., 2006).

Temperature estimates from $\delta^{18}O$ and Mg/Ca ratios are based on single specimens of foraminifera. Two planktic genera, *Morozovella* and *Subbotina*, are used as indicators for near surface (SST) and thermocline (~400 m) temperature, respectively (Pearson et al., 2006). The benthic genus *Cibicides* is used as an indicator for seafloor temperature, which is thought to represent intermediate water in this lower bathyal setting. Foraminiferal preservation is variable but is generally better in the lower part of the section, with pores and ornamentation preserved on surfaces and microgranular layering preserved in walls. Recrystallization has resulted in loss of some surface features and wall structures in the upper part of the section. Some specimens are also infilled with secondary calcite. While recrystallization makes some of the $\delta^{18}O$-based temperature estimates questionable, the method used for Mg/Ca analysis has largely circumvented this problem. Mg/Ca analyses were carried out on five samples where foraminifera are

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[1] GSA Data Repository item 2009029, detailed methods, data tables, and additional figures, is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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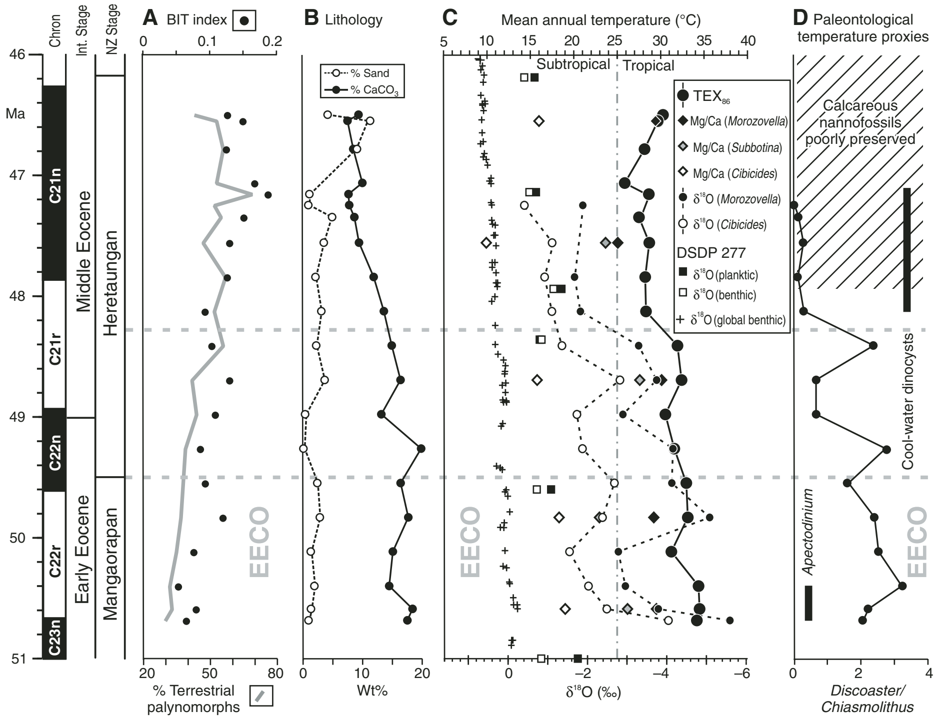

Figure 1. Variation in environmental proxies within Eocene Ashley Mudstone, mid-Waipara River. A: Terrestrial input recorded by percentage of terrestrial palynomorphs and branched to isoprenoidal tetraether (BIT) index. B: Mudstone lithology variation recorded by percentage of sand-sized detrital grains and carbonate. C: Estimated mean annual marine temperatures derived from mean $\delta^{18}O$ measurements from multiple individual specimens of foraminifera genera *Morozovella* (sea surface) and *Cibicides* (seafloor), mean Mg/Ca ratios from multiple ablation holes in multiple specimens of foraminiferal genera *Morozovella*, *Subbotina* (thermocline) *Cibicides*, and TEX_{86} measurements from organic matter. Planktic and benthic $\delta^{18}O$ record for Deep Sea Drilling Project (DSDP) Site 277 (Shackleton and Kennett, 1975) and global benthic $\delta^{18}O$ compilation (Zachos et al., 2001) are also shown. D: Dinocyst and calcareous nannofossil paleotemperature indicators. Cooling steps ca. 49.5 and ca. 48.3 Ma are indicated by dashed gray line.

well preserved. Elemental abundances are determined by laser ablation–inductively coupled plasma–mass spectrometry. Analysis includes multiple measurements of multiple ablated holes in individual specimens of *Morozovella*, *Subbotina*, and *Cibicides*. Specific holes or zones within holes are screened for diagenetic alteration or detrital contamination by identifying anomalous Mg/Ca, Al/Ca, Mn/Ca, and Sr/Ca ratios. Temperature estimates are based on screened Mg/Ca values averaged for multiple holes on multiple specimens of a given taxon within a sample. Sea temperatures are calculated using the exponential relationship between Mg/Ca and temperature [Mg/Ca (mmol/mol) = $A \times e^{B \times T}$]. Temperatures are calculated using the mean calibration for nine modern planktic species (A = 0.38, B = 0.09; Anand et al., 2003) and three benthic species (A = 0.867, B = 0.109; Lear et al., 2002) and the conservative assumption that Eocene seawater Mg/Ca was 3.85 (35% lower than present Mg/Ca of 5.2; Lear et al., 2002). The lower values for Paleogene seawater Mg/Ca suggested by fossil echinoderm studies (Dickson, 2002) would lead to significantly higher sea temperatures than reported here.

Stable isotope analyses of single specimens of *Morozovella* and *Cibicides* from 15 samples utilized an Autocarb coupled to a PRISM mass spectrometer. Precision, based on replicate analyses of in-house standard CM (Carrera marble), is better than ±0.05 and ±0.10 for $\delta^{13}C$ and $\delta^{18}O$, respectively. All values are reported relative to Vienna Peedee belemnite. Temperature is estimated using the equation of Erez and Luz (1983) with an ice-free $\delta^{18}O_{seawater}$ value of −1‰ (Zachos et al., 1994). No corrections are made for surface-water salinity or other isotopic fractionation effects.

Analytical methods are detailed and all data are tabulated in the GSA Data Repository.

AGE AND DEPOSITIONAL SETTING

The EECO is defined by an early Eocene minimum in global $\delta^{18}O$ that ranges from 53 to 51–49 Ma (Zachos et al., 2001). It is broadly equivalent to the New Zealand Mangaorapan Stage (53–49.5 Ma; Cooper, 2004). Biostratigraphy for the 60-m-thick Ashley Mudstone section places the boundary between the Mangaorapan and overlying Heretaungan Stage 20 m above the base of the section (Fig. DR2). An unconformity between the Heretaungan and overlying Bortonian 10 m below the top of the section indicates that the intervening Porangan Stage (46.2–43 Ma) is missing. The Mangaorapan–Heretaungan interval is correlated to upper NP12 to NP14–NP15 calcareous nannofossil zones. The uppermost Bortonian sample contains an NP16 assemblage. An age/depth plot based on six datums (Fig. DR2) indicates that the lower 50 m of section extends from 50.7 to 46.5 Ma.

Paleobathymetric indicators within the benthic foraminiferal assemblages, including *Anomalinoides semicribratus*, *A. capitatus*, *Nuttallides carinotruempyi*, and *Pleurostomella* spp., indicate a lower bathyal depositional depth (van Morkhoven et al., 1986). Because terrestrial palynomorphs compose >30% of the palynomorph assemblage (Fig. 1A), a steep west to east shelf-slope profile is inferred for the northern Canterbury basin. Terrestrial palynomorph abundance covaries with the BIT index and both indicate an upward increase in terrigenous input (Fig. 1A). This increase in terrestrial input is associated with a decrease in carbonate content and an increase in detrital sand (Fig. 1B), which may be due to increased winnowing of the mud fraction by bottom currents, a decrease in biogenic carbonate production, increased carbonate dissolution, or a combination of these factors.

PALEOTEMPERATURE

The three paleotemperature proxies are in good agreement, despite variable preservation of foraminifera and its likely effect on the $\delta^{18}O$ record (Fig. 1C). TEX_{86} and planktic Mg/Ca indicate tropical conditions (annual SST >25 °C) for the northern Canterbury Basin from the early to middle Eocene (50.7–46.5 Ma). SST peaked at 30–35 °C at 50.7–48.4 Ma and declined to 25–30 °C at 48.2–46.5 Ma. The planktic $\delta^{18}O$ record is variable but generally consistent with this trend. For two intervals where comparatively greater cooling is recorded (ca. 50.4 and ca. 48.2 Ma), the $\delta^{18}O$ shift may have been amplified by diagenesis. Overall, TEX_{86} indicates somewhat warmer temperatures than planktic Mg/Ca and $\delta^{18}O$. As all three proxies are calibrated to mean annual temperature, such differences probably reflect uncertainties in the assumptions underlying the temperature estimates. For example, TEX_{86} and Mg/Ca temperature estimates would be in closer agreement if Eocene seawater Mg/Ca was >35% lower than present day (e.g., Dickson, 2002).

Benthic Mg/Ca and $\delta^{18}O$ record a gradual decline in seafloor water temperature. The low-resolution Mg/Ca data show a gradual temperature decline from 19 to 16 °C from the early to middle Eocene. An anomalously low value of 10 °C at 47.6 Ma is unreliable because the specimen is poorly preserved. Benthic $\delta^{18}O$ is variable in the lower part of the section, ranging from

20 to 32 °C. Strongly negative values, suggesting seafloor temperatures >25 °C, are probably artifacts of diagenetic mixing with isotopically lighter carbonate from planktic foraminifera or calcareous nannofossils. If these extreme values are excluded, the combined benthic Mg/Ca and δ^{18}O trend indicates a gradual decline in intermediate water temperature from 19–24 °C ca. 50 Ma to 16 °C ca. 48 Ma.

A consistent separation in Mg/Ca ratios between the near surface-dwelling, thermocline-dwelling, and bottom-dwelling foraminiferal genera (*Morozovella*, *Subbotina*, and *Cibicides*) provides further support for the Mg/Ca-based temperature estimates and implies a relatively constant surface to seafloor temperature gradient of 10–15 °C, or ~1 °C/100 m, which is comparable to modern tropical continental margin settings (http://www.nodc.noaa.gov).

To ascertain the regional extent of this tropical water mass, we compare the mid-Waipara record to the δ^{18}O record from Deep Sea Drilling Project (DSDP) Site 277 (Shackleton and Kennett, 1975), which has been widely used for regional marine paleotemperature reconstructions (e.g., Kennett, 1978; Nelson and Cooke, 2001; Kennett and Exon, 2004). In the Eocene, Site 277 was situated at ~65°S on the western margin of the Campbell Plateau (Fig. DR1) at middle to lower bathyal water depths (Hollis et al., 1997). Benthic δ^{18}O data from the site indicate that seafloor temperature was remarkably stable from the early to middle Eocene, hovering at 15 °C from 51 to 46 Ma (Fig. 1C). It is significant that seafloor temperatures from Site 277 and mid-Waipara converge in the middle Eocene from 48.3 to 46.5 Ma. However, in striking contrast to mid-Waipara, the planktic-benthic temperature gradient at Site 277 is very weak in the early Eocene and negligible in the middle Eocene. Given the similarities between the two sites in paleodepth and seafloor temperature estimates, we contend that the Site 277 planktic δ^{18}O record has been overprinted by seafloor carbonate during early diagenesis. Examination of Eocene planktic foraminifera from this site has confirmed the presence of calcite overgrowths. For low latitudes, Pearson et al. (2007, p. 213) determined that the degree of diagenetic overprint in planktic tests increased through the Eocene as "bottom waters became more undersaturated, colder and more corrosive." Similarly, deep-water cooling would account for the reduced planktic-benthic offset at both Site 277 and mid-Waipara ca. 48.3 Ma. At mid-Waipara, this event was accompanied by surface water cooling, as is evident from TEX$_{86}$ and changes in dinocyst and calcareous nannofossil assemblages (Figs. 1C and 1D). A coeval decrease in carbonate content and calcareous nannofossil preservation and a small increase in detrital sand (Figs. 1B and 1D) are consistent with an incursion of corrosive deep water. An increase in terrestrial input (Fig. 1A) may be a local response to cooler climatic conditions.

As noted above, the mid-Waipara SST trend is reflected in changes in dinocyst and nannofossil assemblages (Fig. 1D). The early Eocene interval of peak warmth contains the last occurrence of the warm-water dinocyst genus *Apectodinium*. Elements of a cool-water Transantarctic dinocyst flora (Wrenn and Hart, 1988), including *Spinidinium* cf. *macmurdoense* and *Senegalinium* cf. *assymetricum*, first appear in the middle Eocene at 48.2 Ma. Similarly, the ratio of the warm-water nannofossil genus *Discoaster* to cool-water *Chiasmolithus* peaks in the early Eocene and plummets at 48.2 Ma. These fossil events suggest that for the Canterbury Basin the termination of the EECO occurred in the earliest Heretaungan, between 49.5 and 48.3 Ma. Whereas the EECO appears to have begun at about the same time worldwide (ca. 53 Ma), its termination varies considerably by region. In the equatorial Indian Ocean, it may well have persisted into the late Eocene (Pearson et al. 2007).

DISCUSSION

Paleotemperature estimates from TEX$_{86}$, Mg/Ca, and δ^{18}O at mid-Waipara indicate that climatic conditions at the Canterbury Basin were tropical from the late-early to early-middle Eocene (50.7–46.5 Ma), with peak temperatures in the Mangaorapan and earliest Heretaungan (50.7–48.3 Ma). Although there are no definitive records of fully tropical fossil assemblages from early Eocene New Zealand, there are numerous examples of subtropical to tropical floral and faunal incursions. These include occurrences of the mangrove palm *Nypa* in the Taranaki, East Coast, and Canterbury Basins and occurrences of larger foraminifera (*Asterocylina speighti*, *Amphistegina eyrei*) and warm-water mollusks (*Quadrilatera*, *Septifer*, *Spondylus*, *Cypraea*, and *Eocithara*) in shallow-marine Mangaorapan sediments in the Canterbury Basin and eastern Chatham Rise (Adams et al., 1990; Beu and Maxwell, 1990; Hornibrook, 1992).

Despite this support from the fossil record, SSTs in excess of 30 °C at 55°S seem unrealistic, even allowing for coastal waters being somewhat warmer than the open ocean at the same latitude (Zachos et al., 2006). Peak SSTs at mid-Waipara are higher than modern tropical temperatures and as warm as those inferred for the early Eocene equatorial Pacific (Tripati et al., 2003). However, the SSTs are consistent with the warm deep-water temperatures of 14–22 °C for mid-Waipara and DSDP Site 277. Moreover, the revised calibration for TEX$_{86}$ (Kim et al., 2008) implies SSTs of 35–40 °C for the equatorial Indian Ocean in the Eocene (Pearson et al., 2007). If these estimates are correct, a thermal gradient of <10 °C over 55° of latitude presents a tremendous challenge for ocean circulation models. Even under hypergreenhouse conditions (2240 ppm CO_2), a new coupled ocean-atmosphere general circulation model cannot generate mean annual SST >20 °C for the New Zealand region, or mean summer SST >25 °C (Fig. 2). Under this and similar earlier simulations (Huber and Sloan, 2001; Huber et al., 2004), a strong cyclonic gyre blocks southward transport of subtropical-tropical water beyond 45°S. In contrast, modeled SSTs for the South Atlantic are consistent with an estimated SST of ~15 °C for the early Eocene of Seymour Island (Ivany et al., 2008).

It may be that early Eocene New Zealand's tropical warmth was a localized phenomenon, perhaps linked to the southward penetration of the subtropical East Australian Current, as suggested by Kennett (1978; Kennett and Exon, 2004) and as argued against by Huber et al. (2004). However, similar discrepancies between data and models have been described for the Paleocene-Eocene thermal maximum when Arctic surface waters warmed to >25 °C and the mid-latitude northwest Atlantic warmed to >35 °C (Sluijs et al., 2006; Zachos et al., 2006; TEX$_{86}$-based SST recalculated according to Kim et al., 2008). Therefore, it seems increasingly likely that a poorly known heat transport mechanism, or combination of mechanisms, comes into play in times of extreme global warming. Contenders include ocean switches and gateways (Nunes and Norris, 2006), possibly facilitated by associated rising sea levels; polar stratospheric clouds, which would warm the poles and reduce latitudinal gradients (Sloan and Pollard, 1998); and increased heat transport by tropical cyclones (Korty et al., 2008).

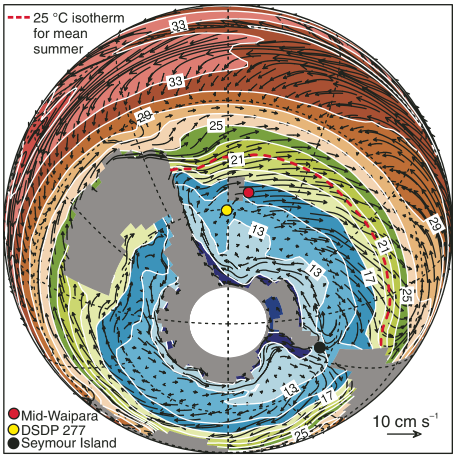

Figure 2. Modeled mean annual ocean circulation and sea-surface temperatures (°C) for southwest Pacific and Southern Oceans during early Eocene based on coupled ocean-atmosphere simulation for 2240 ppm CO_2 (National Center for Atmospheric Research, NCAR-CCSM3). DSDP—Deep Sea Drilling Project.

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