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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 CO₂), 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 foraminifers 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, TEX₈⁶ (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 (Schrarg, 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 surfacewater temperature in deep sea cores. New multiproxy evidence for hypothermal 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 pCO₂ for the early Eocene, which ranges from 800 to 2500 ppm (Pearson and Palmer, 2000) to >1125 ppm (Lovenstein and Demicco, 2006). For the low-latitude Pacific, surface temperatures of >30 °C 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 TEX₈⁶, Mg/Ca, and δ¹⁸O 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). 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.

TEX₈⁶ temperature estimates are based on the relative distribution of archaeal glycerol dialkyl glycerol tetraether (GDGT) marine lipids (Schouten et al., 2002, 2007). Conversion of TEX₈⁶ 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 TEX₈⁶ is not biased by contributions from soil archaea (Weijers et al., 2006).

Temperature estimates from δ¹⁸O 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 δ¹⁸O-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
The EECO is defined by an early Eocene minimum in global δ¹⁸O that ranges from 53 to 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.

Paleobiometric indicators within the benthic foraminiferal assemblages, including Anomaloinoides semicribratus, A. capitatus, Nuttallides carinonuropymi, 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.
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 δ18O 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 δ18O 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 Exxon, 2004). In the Eocene, Site 277 was situated at ~65°S on the western margin of the Campbell Plateau (Fig. DR1) at 49.5–48.3 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 TEX86, Mg/Ca, and δ18O 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 Manganopan and earliest Heretaunga (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 (Asterocylinia speighti, Amphistegina eyrei) and warm-water mollusks (Quadrilatera, Septifer, Spondylus, Cypraea, and Eothealis) in shallow-marine Manganopan 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 TEX86 (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 CO2), 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 Exxon, 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; TEX86-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).
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