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LETTERS

Early Palaeogene temperature evolution of the southwest Pacific Ocean

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Relative to the present day, meridional temperature gradients in the Early Eocene age (∼56–53 Myr ago) were unusually low, with slightly warmer equatorial regions[1] but with much warmer subtropical Arctic[2] and mid-latitude[3] climates. By the end of the Eocene epoch (∼34 Myr ago), the first major Antarctic ice sheets had appeared[4,5], suggesting that major cooling had taken place. Yet the global transition into this icehouse climate remains poorly constrained, as only a few temperature records are available portraying the Cenozoic climatic evolution of the high southern latitudes. Here we present a uniquely continuous and chronostratigraphically well-calibrated TEX$_{86}$ record of sea surface temperature (SST) from an ocean sediment core in the East Tasman Plateau (palaeolatitude ∼65° S). We show that southwest Pacific SSTs rose above present-day tropical values (to ∼34 °C) during the Early Eocene age (∼53 Myr ago) and had gradually decreased to about 21 °C by the early Late Eocene age (∼36 Myr ago). Our results imply that there was almost no latitudinal SST gradient between subequatorial and subpolar regions during the Early Eocene age (55–50 Myr ago). Thereafter, the latitudinal gradient markedly increased. In theory, if Eocene cooling was largely driven by a decrease in atmospheric greenhouse gas concentration[6], additional processes are required to explain the relative stability of tropical SSTs given that there was more significant cooling at higher latitudes.

The Palaeogene temperature evolution of the Antarctic margin, particularly the Pacific sector, is still poorly resolved. One difficulty with obtaining relevant records close to the Antarctic continent is the general absence of biogenic carbonate in most marine facies, which hampers traditional δ^{18}O and/or Mg/Ca-based reconstructions of the subpolar temperature evolution. In the absence of biogenic carbonates, organic sea-surface-temperature proxies such as the tetraether index of lipids consisting of 86 carbon atoms (TEX$_{86}$)[7] and the alkenone unsaturation index (U$^{k'}_{37}$)[8] are required for reconstructing high-latitude climatic evolution[2,9].

We apply TEX$_{86}$ and U$^{k'}_{37}$ on a stratigraphically continuous sedimentary section from the southwest Pacific Ocean, drilled by the Ocean Drilling Program (ODP Leg 189 Site 1172, palaeolatitude ∼65° S (ref. 10); Fig. 1). A full methodological description is available in Supplementary Information. The record contains an expanded succession of marginal marine sediments from the lower Palaeocene epoch to the upper Eocene (64–36 Myr ago), with tight chronostratigraphic control, including magnetostratigraphy[11] (Supplementary Fig. 2). The presence of typical trans-Antarctic organic-walled dinoflagellate cysts in the Tasman region indicates an Antarctic-derived northward-flowing Tasman Current throughout the Palaeogene, which is verified by experiments based on general circulation models[12] (Fig. 1). This Antarctic influence at the East Tasman Plateau (ETP) persisted until at least the early Late Eocene (∼35.5 Myr ago), when deepening of the Tasmanian Gateway lead to a reorganization of the Tasman and proto-Leeuwin ocean currents[13].

According to the oldest part of the record, TEX$_{86}$-derived SSTs at the ETP gradually decreased from ∼25 °C around 63 Myr ago to a minimum of ∼20 °C around 58 Myr ago (Fig. 2a). During the Late Palaeocene and Early Eocene, Tasman SSTs gradually rose to tropical values of ∼34 °C during the Early Eocene climatic optimum (EECO)[6], between 53 and 49 Myr ago (Fig. 2a). A gradual cooling trend throughout the Middle Eocene (starting at the termination of the EECO ∼49 Myr ago) arrived at temperatures of ∼23 °C ∼42 Myr ago, which is still relatively warm. Subsequently, an interruption of the cooling trend occurred at the Middle Eocene climatic optimum (MECO; ∼40 Myr ago)[14], followed by a relatively rapid SST decrease to ∼21 °C in the early Late Eocene (Fig. 2a). The late Middle and Late Eocene TEX$_{86}$-based SSTs are supported by U$^{k'}_{37}$ SST estimates derived from the same samples (Supplementary Fig. 3). Both SST estimates also compare well with those for other Late Eocene (Southern Ocean) sites[9]. Unfortunately, sediments from the ETP older than the MECO did not contain alkenones for U$^{k'}_{37}$ SST reconstructions.

The Middle Eocene SSTs correspond closely to those from sections in New Zealand[15,16], according to records based on TEX$_{86}$ (Fig. 2a), Mg/Ca and δ^{18}O, indicating regional consistency of our reconstructed SSTs. Also, trends in our Tasman SST record are remarkably similar to those in the global stack of benthic foraminiferal oxygen isotopes[6] (Fig. 2b), which we updated and augmented with recently published

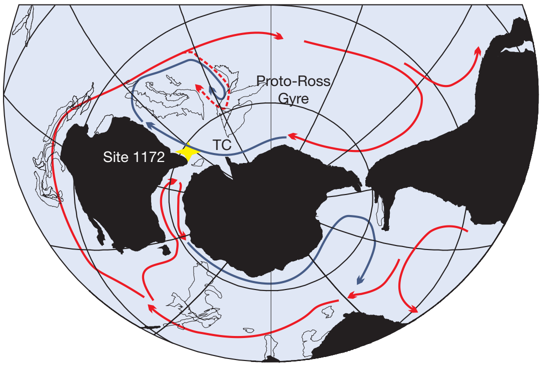

Figure 1 | Site location and surface currents. Palaeogeographic reconstruction for the South Pacific Ocean at Early–Middle Eocene times. Surface circulation[12] indicates the Antarctic-derived Tasman Current (TC) over the East Tasman Plateau. Palaeogeographic charts obtained from the Ocean Drilling Stratigraphic Network (ODSN); after ref. 26. The dashed red arrow around New Zealand indicates potential mixing of low-latitude surface waters (from the East Australian Current) with the TC.

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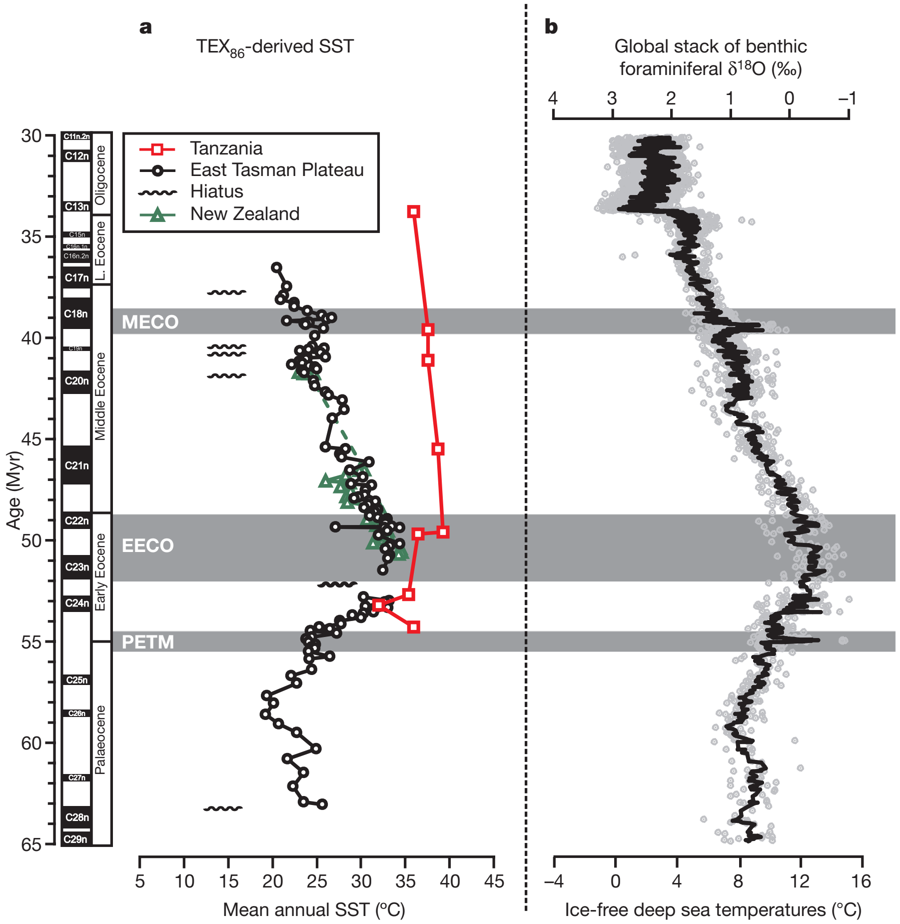

Figure 2 | Palaeogene deep-sea and sea surface temperatures. a, TEX$_{86}$ SST reconstructions from ODP Site 1172, New Zealand[15,16] and Tanzania[1] (all according to the same calibration; see Supplementary Information). The black wiggly lines are short (~100 kyr)[27] and longer hiatuses at Site 1172. **b**, Global stack of benthic foraminiferal oxygen isotopes (grey data; Supplementary Information). The temperature scale assumes ice-free conditions ($\delta^{18}O_{SMOW} = -1.2$‰, where $\delta^{18}O_{SMOW} = (^{18}O/^{16}O)_{sample}/(^{18}O/^{16}O)_{SMOW} - 1$; SMOW, standard mean ocean water), and indicates deep-sea temperatures. The black solid line reflects a five-point running average. PETM, Palaeocene–Eocene thermal maximum.

data (Supplementary Information). This correspondence between the two records (Supplementary Fig. 4) indicates that the regional SSTs co-varied with the SSTs where 'global' deep water was sourced. It has previously been suggested that the Southern Ocean was the main region of deep-water formation during the Palaeogene[17].

In contrast, absolute SST estimates from the Tasman region are much higher than those inferred from the benthic foraminiferal oxygen isotopes (Fig. 2). Part of this discrepancy might be due to seasonality, with TEX$_{86}$ being slightly skewed towards summer temperatures and benthic foraminiferal δ^{18}O towards winter temperatures (Supplementary Information). Another possibility is that deep-water formation occurred in areas that were cooler than the Tasman sector. SST reconstructions based on bivalve-shell oxygen isotopes from Seymour Island on the Antarctic shelf, for example, yield much lower SSTs[18]. It is possible that the Antarctic margin was more susceptible to winter cooling than the open ocean, or that portions of the coast along the Antarctic sector were somehow isolated from the southern edges of the Southern Ocean gyres. Another possibility is that the aragonite bivalve shells integrate temperature over a greater portion of the year. Regardless, the large SST difference between the Weddell Sea and the ETP would suggest a relatively steep gradient within a few degrees of latitude. Antarctica, being a polar continent, would most likely have experienced extremes in temperature, in particular having cool winters. Such conditions might have been recorded in the bivalves from the Weddell Sea but not in the more distal ETP. In turn, deep-water formation might have been restricted to the Antarctic shelf areas, such as the Weddell Sea.

Planktonic foraminiferal δ^{18}O analyses from equatorial regions previously indicated that Palaeogene low-latitude SSTs were the same, or even lower, than those of today[19], a problem that puzzled palaeoclimate scientists for decades. The oxygen isotopic composition of planktonic foraminiferal tests in porous carbonate-rich pelagic facies were later found to be partially altered owing to recrystallization primarily during early diagenesis[20,21]. In contrast, carbonate-poor and clay-rich facies typically found on the continental margins contain calcite shells without major diagenetic overprint[1]. For the Eocene, such well-preserved planktonic foraminifera indicate near-equatorial SSTs that were greater than those of the present day, and agree with TEX$_{86}$-derived SSTs[1,21].

Another observation from well-preserved foraminifera and TEX$_{86}$ is that (sub)equatorial SSTs were remarkably stable throughout the Eocene[1] (Fig. 2). Stable low-latitude SSTs concomitant with high-latitude Eocene cooling thus suggests that there were increasing SST gradients during the Eocene. Although SST trends are often reconstructed using multi-proxy studies, the difference in absolute SSTs between various proxy reconstructions can be considerably large[9,15,22], even when measured on the same sediments. Despite the fact that multi-proxy approaches are generally encouraged in palaeoclimate studies, exclusion of such inter-proxy biases in latitudinal gradient reconstructions requires single-proxy SST records from around the world. Traditional calcite-based SST reconstructions are less suitable for this because calcite is only sparsely available in high-latitude sediments. The organic TEX$_{86}$ and $U^{k'}_{37}$ SST proxies, however, can be used independently of latitude and are, hence, suitable for single-proxy SST gradient reconstructions. Moreover, they do not require critical assumptions about ancient sea-water chemistry, unlike δ^{18}O and Mg/Ca.

We compiled Eocene TEX$_{86}$ and U$^{k'}_{37}$ SST reconstructions from a suite of sedimentary records from localities worldwide and noted increased Middle Eocene latitudinal SST gradients in both hemispheres (Fig. 3), relative to the Early Eocene. These SST gradients are in general agreement with those found for terrestrial mean annual temperatures, based on Early–Middle Eocene fossil leaves[23]. Adding the bivalve-based SST reconstructions from Seymour Island[18] to our organic proxy data suggests a strong gradient between 60° and 70° S, which contrasts with the small gradient between 60° S and the Equator (Fig. 3). A part of this large Southern Ocean SST gradient might be due to biases between organic and calcite proxies. A large part, however, may realistically reflect the influence of the cool Antarctic interior, which cooled the Antarctic shelf. In contrast to the continental South Pole, the Arctic region is an oceanic basin. Instead of amplifying the seasonal cycle, the Arctic Ocean probably moderated seasonal extremes in the northern high-latitude greenhouse. Hence, Palaeogene latitudinal temperature gradients, like those of today, would have exhibited a high degree of asymmetry between the two hemispheres.

It has been suggested that the general warmth that characterized early Palaeogene climates was forced by high atmospheric greenhouse gas concentrations[6]. Concomitantly, the absence of polar ice sheets eliminated ice–albedo feedbacks in the Palaeogene greenhouse. The Middle–Late Eocene global cooling has been related to long-term atmospheric CO$_2$ decline, eventually resulting in the onset of major Antarctic glaciation around the Eocene/Oligocene boundary[6]. Our results imply that meridional temperature gradients markedly increased together with deep-sea cooling (Fig. 2)[6]. Although high latitudes cooled, tropical temperatures seem to have remained fairly stable throughout the Eocene (Fig. 3)[1]. This observation raises questions concerning the precise role of decreasing atmospheric greenhouse gas concentrations in cooling the Eocene poles, as in theory[24] they should have cooled tropical regions as well. The role of potential high-latitude climate feedbacks involving, for example, differences in cloud/water vapour distribution[25] might have been much more instrumental in the Middle Eocene climatic deterioration than previously thought. Another potential positive-feedback mechanism for high-latitude cooling would be ice–albedo feedback. However, the presence of substantial Middle Eocene continental ice is still equivocal given the general warmth and overall absence of conclusive physical evidence.

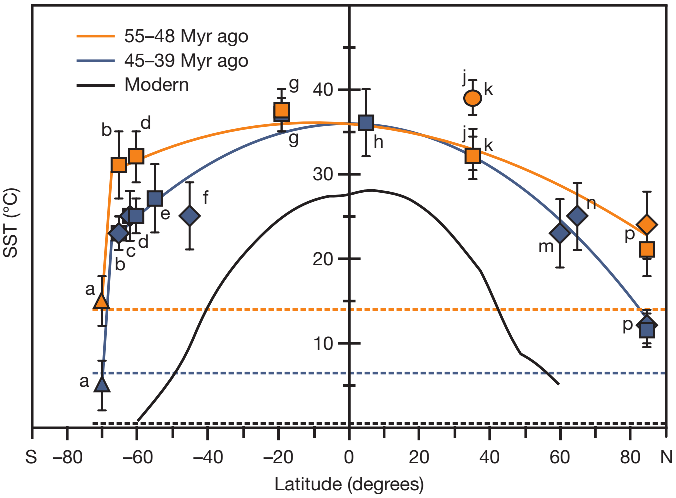

Figure 3 | Early and Middle Eocene latitudinal SST gradients. Bivalve-shell δ^{18}O (triangles), TEX$_{86}$ (squares) and U$^{k'}_{37}$ (diamonds) SST reconstructions for the Early (orange) and mid-Middle (blue) Eocene. Data are from Seymour Island[18] (a), the East Tasman Plateau (b), Deep Sea Drilling Project (DSDP) Site 277[9] (c), New Zealand[15,16] (d), DSDP Site 511[9] (e), ODP Site 1090[9] (f), Tanzania[1] (g), ODP Site 925[9] (h), New Jersey[3] (j, k; circle represents peak PETM SSTs[3]), ODP Site 336[9] (m), ODP Site 913[9] (n) and the Arctic Ocean[2,28,29] (p) (Supplementary Fig. 1). Error bars indicate the range of variation. Gradients represent second-order polynomials, excluding bivalve-shell data. Black and dashed lines represent the present-day zonally averaged latitudinal temperature gradient[30] and age-specific deep-sea temperatures, respectively (Fig. 2b, ref. 6).

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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