

Jiggling the tropical thermostat in the Cretaceous hothouse

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ABSTRACT

Modern open-ocean sea-surface temperatures rarely exceed $\sim 28\text{--}29^\circ\text{C}$, and the same has been thought to represent a rough maximum for past tropical climates. However, new isotopic estimates from the uppermost Cenomanian in the tropical western North Atlantic suggest that mixed-layer temperatures reached $\sim 33\text{--}34^\circ\text{C}$ ($\pm 2^\circ\text{C}$) during the middle Cretaceous hothouse. Uppermost Cenomanian tropical sea-surface temperatures may have been as much as $4\text{--}7^\circ\text{C}$ warmer than the highest modern mean annual temperatures. Such extreme conditions suggest that warm tropical oceans could have driven substantially intensified atmospheric heat transport near the Cenomanian-Turonian boundary. The tropical “thermostat” was set higher than today, challenging the hypothesis of tropical climate stability.

Keywords: temperature, Cretaceous, planktonic foraminifera, stable isotopes, Atlantic.

INTRODUCTION

The magnitude of climate change from the middle Cretaceous to today is perhaps best illustrated by $\delta^{18}\text{O}$ -based paleothermometric records in deep-sea foraminiferal calcite showing that subantarctic sea-surface temperatures (SSTs) during some intervals (e.g., Cenomanian, ca. 95 Ma) were $\sim 20^\circ\text{C}$ warmer than today (Huber et al., 1995; Huber and Hodell, 1996). Paradoxically, however, most equivalent Cretaceous records from low-latitude sites suggest that contemporaneous SSTs in the tropics were no warmer than or were even cooler than today (Crowley and North, 1991; Price et al., 1998; Crowley and Zachos, 2000). Some authors have suggested that these cool tropical SSTs are accurate measurements of paleo-SSTs that require a reevaluation of Cretaceous climates (Sellwood et al., 1994; D'Hondt and Arthur, 1996). Others have suggested that cool tropical SSTs are an artifact arising from severe underestimation of Cretaceous global ice volumes and that, in reality, low-latitude SSTs have not changed significantly since 100 Ma but have instead been “thermostated” to modern values ($\sim 28\text{--}29^\circ\text{C}$; Matthews and Poore, 1980; Prentice and Matthews, 1988).

Middle Cretaceous strata contain abundant indications of extreme global warmth with some lines of evidence (e.g., crocodylians in the Canadian arctic [Huber, 1998] and fossil breadfruit trees in Greenland [Nathorst, 1911]) so compelling that the poles were most likely free of large-scale continental ice caps. We argue that cool tropical SST estimates for the Cretaceous are an artifact arising from inappropriate estimates of the isotopic composition of seawater (Zachos et al., 1994; Poulsen et al., 1999) as well as the analysis of inade-

quately preserved and/or subsurface dwelling foraminifera (Wilson and Opdyke, 1996; Norris and Wilson, 1998; Pearson et al., 2001). The latter studies provide good evidence of tropical SSTs having been at least as warm as today. However, a combination of paleolatitude considerations and uncertainties involved in $\delta^{18}\text{O}$ -based paleothermometry make it difficult to establish whether core tropical SSTs were actually significantly warmer than those

of the present day (Barron and Peterson, 1991; Crowley and Zachos, 2000).

METHODS

Deep Sea Drilling Project (DSDP) Site 144 ($9^\circ 27'\text{N}$, $54^\circ 21'\text{W}$; 2957 m water depth) was spot-cored on the outermost edge of Demerara Rise off the coast of Suriname (Cenomanian paleolatitude was $\sim 5^\circ\text{N}$; Smith et al., 1994). Drilling recovered upper Cenomanian to Coniacian black shales at shallow burial depth ($\sim 180\text{--}220$ m below sea floor [mbsf]). Constituent foraminifera are predominantly planktonic; the assemblage consists of abundant, but small, planktonic foraminifera in the genera *Hedbergella*, *Heterohelix*, and *Globigerinelloides* as well as rich nannoplankton assemblages (Hayes et al., 1972).

Stable isotope analyses were performed at Woods Hole Oceanographic Institution on single-species samples of *Hedbergella delrioensis*, *Heterohelix moremani*, *Whiteinella* sp., and *Globigerinelloides bentonensis* from the 125–150 μm size fraction (Fig. 1). Approxi-

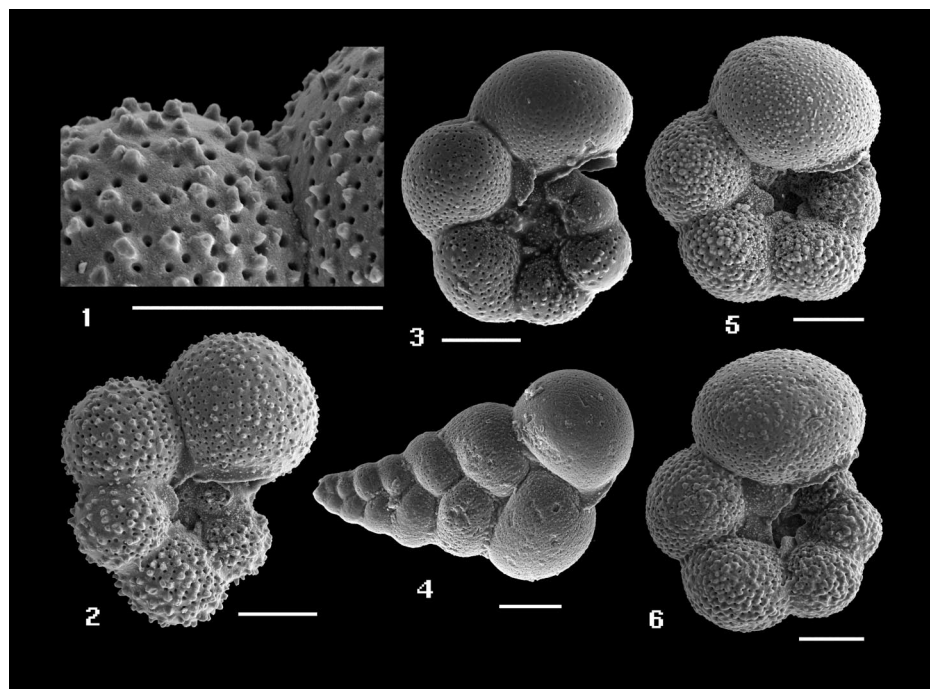


Figure 1. Scanning electron micrograph images of foraminifera analyzed from Deep Sea Drilling Project Site 144. All scale bars represent $50\ \mu\text{m}$. 1–2: *Hedbergella delrioensis*; 3: *Globigerinelloides bentonensis*; 4: *Heterohelix moremani*; 5–6: *Whiteinella* sp. Note extremely well preserved wall texture in 1. Specimens are from sample 144-4H-3, 72–75 cm.

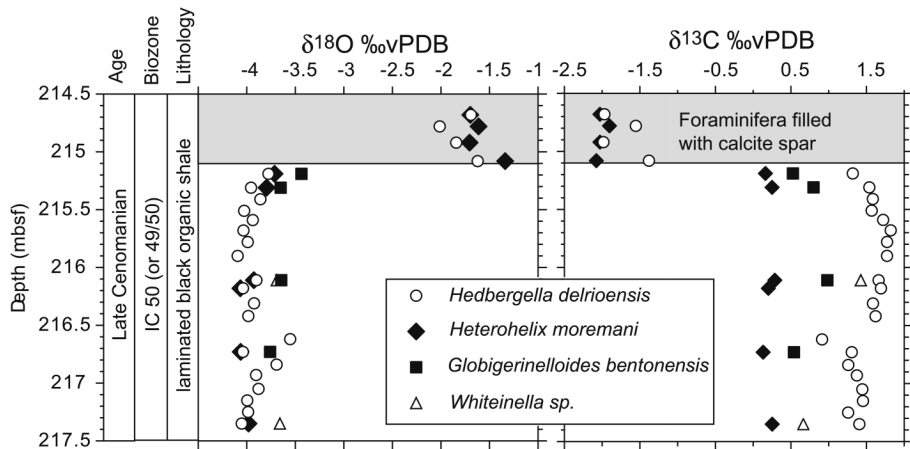


Figure 2. Stable isotope data for cores DSDP144-4H-2 and DSDP144-4H-3. Shaded interval represents samples with well-preserved, but calcite spar-filled foraminifera. All other samples display pristine preservation without in-filling calcite. VPDB is Vienna Pee Dee belemnite; mbsf is meters below seafloor.

mately 20–60 specimens were analyzed in each sample to provide a good estimate of the population mean isotopic ratios. Ostermann and Curry (2000) described the instrument precision and methods of data correction for our mass spectrometer. Isotope data are reported relative to the Vienna Pee Dee belemnite (VPDB) isotope standard.

RESULTS

On the basis of the nannoplankton assemblage, the sediments in Core 144-4 are as-

signed to integrated microfossil zones IC 50-51 (Bralower et al., 1995; T.J. Bralower, 2001, personal commun.) of the uppermost Cenomanian. The absence of rotaliporids suggests that the samples belong to the latest Cenomanian (IC zone 50; 93.5–94 Ma), postdating the global extinction of rotaliporids.

Planktonic foraminifera in the 20 samples below 215.1 mbsf exhibit superb preservation, as exemplified by their glassy appearance, hollow chambers, preservation of surface ornamentation without overgrowths, and micro-

tabular structure of the shell walls (Fig. 1). Observation with a scanning electron microscope confirms that the chambers of foraminifera between 215.3 and 217.5 mbsf are not filled with diagenetic calcite and are texturally pristine. In contrast, foraminifera associated with thin stringers of carbonate-rich claystone in the uppermost four samples (214.8–215.1 mbsf) are outwardly well preserved, but are completely filled with clear calcite spar.

Well-preserved middle Cretaceous planktonic foraminifera from Demerara Rise yield remarkably consistent stable isotope values within species (Fig. 2). *Hedbergella delrioensis* yielded the most negative $\delta^{18}\text{O}$ value (-4.09‰) and an average ratio of $-3.91\text{‰} \pm 0.15\text{‰}$ ($N = 20$). The other species produced similarly very negative $\delta^{18}\text{O}$ ratios: *Heterohelix moremani* ($-3.94\text{‰} \pm 0.14\text{‰}$, $N = 6$); *Globigerinelloides bentonensis* ($-3.64\text{‰} \pm 0.14\text{‰}$, $N = 4$); and *Whiteinella* sp. ($-3.69\text{‰} \pm 0.03\text{‰}$, $N = 2$). In contrast, our $\delta^{13}\text{C}$ data show significant differences among species and through geologic time. Well-preserved populations of *Hedbergella delrioensis* have the most positive $\delta^{13}\text{C}$ ($+1.50\text{‰} \pm 0.23\text{‰}$, $N = 20$), whereas *Heterohelix moremani* has the most negative values ($+0.21\text{‰} \pm 0.06\text{‰}$, $N = 6$). Samples where the foraminifera are filled with calcite spar have significantly higher $\delta^{18}\text{O}$ values (-2‰ to -1.4‰) and lower $\delta^{13}\text{C}$ values (-2.1‰ to -1.3‰) than the well-preserved samples. The positive $\delta^{18}\text{O}$ and negative $\delta^{13}\text{C}$ ratios of the poorly preserved foraminifera are consistent with infilling by calcite spar at sea-bottom temperatures during oxidation of organic carbon in the black shale.

DISCUSSION

We calculated paleotemperatures first by assuming a value of -1‰ relative to SMOW (standard mean ocean water) or -1.27‰ PDB (Pee Dee belemnite) for the $\delta^{18}\text{O}$ of mean seawater (δ_w) under ice-free conditions (Shackleton and Kennett, 1975) (Fig. 3). Application of three paleotemperature equations (those of Bemis et al., 1998, equations 1 and 2; Erez and Luz, 1983) to the average $\delta^{18}\text{O}$ of *H. delrioensis* (-3.9‰) provides a range of calcification temperatures between 27.5 and 29.5 °C. We favor the highest paleotemperature estimates because they were derived from an equation (Bemis et al., 1998, equation 1) based on calibration of $\delta^{18}\text{O}$ and calcification temperature of asymbiotic planktic foraminifera in culture experiments. In contrast, equation 2 of Bemis et al. (1998) was derived from foraminifera culture experiments, but is based on studies of photosymbiotic foraminifera raised under high illumination to maximize photosynthetic activity.

Albian-Cenomanian *Hedbergella delrioensis*

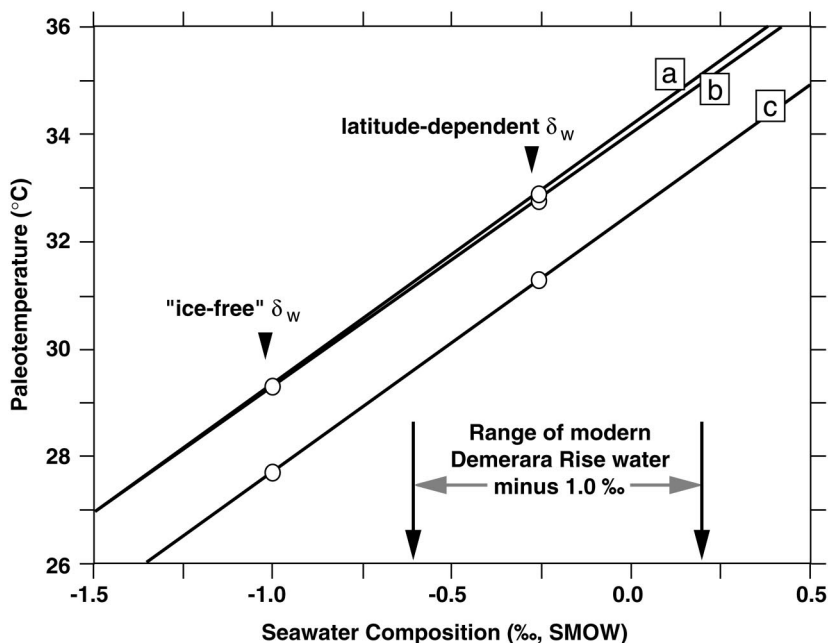


Figure 3. Paleotemperature estimates for Site 144 *Hedbergella delrioensis* ($\delta^{18}\text{O} = -3.94\text{‰}$ relative to Vienna Pee Dee belemnite [VPDB]) as function of estimated ambient seawater oxygen composition (δ_w , relative to standard mean ocean water [SMOW]). Estimates shown were obtained from carbonate isotopic paleotemperature equations of (a) Bemis et al. (1998) equation 1, (b) Erez and Luz (1983), and (c) Bemis et al. (1998) equation 2. Paleotemperature calculations made with $\delta_w = -1\text{‰}$ SMOW ($= -1.27\text{‰}$ PDB) yield systematically cooler temperatures (by $>3\text{ °C}$) compared to calculations made with more realistic, heavier values for tropical δ_w .

sis was an opportunistic species, sometimes recording thermocline waters (Norris and Wilson, 1998) and at other times surface waters (Price et al., 1998). The potential variation in depth habitat suggests that our calculated SSTs could be underestimates. The consistency in $\delta^{18}\text{O}$ values among all the species suggests that they lived in poorly stratified surface waters, perhaps influenced by upwelling conditions that also contributed to organic carbon deposition. Upwelling conditions could also contribute to depressed SSTs. We conclude that our temperature estimates are more likely to be minimums, not maximums.

Norris and Wilson (1998) showed that *H. delrioensis* was asymbiotic, and we suggest that the same may have been true in the late Cenomanian. Therefore, the appropriate equation is the low-illumination relationship (equation 1 of Bemis et al., 1998) that provides a robust estimate of the temperature relationship for planktic foraminifera grown without symbionts. Bemis et al.'s equation 1 yields virtually the same estimated paleotemperature of $\sim 29.3^\circ\text{C}$ as that of Erez and Luz (1983).

All the foregoing paleotemperature estimates are based on the assumption that the $\delta^{18}\text{O}$ of Cenomanian seawater over Demerara Rise was near the global average. Yet, the δ_w of modern ocean water shows a strong correlation with latitude, a relationship produced by geographic differences in evaporation and precipitation (Broecker, 1989; Fairbanks et al., 1992). Today δ_w is systematically higher in the relatively saline Atlantic than it is in the fresher Pacific, and tropical δ_w values are 0.4‰–1.0‰ heavier than the global mean δ_w (Broecker, 1989). Zachos et al. (1994) developed a relationship describing the latitude dependency of δ_w by averaging Pacific and Atlantic data from the Southern Hemisphere.

Today, waters over Demerara Rise are influenced by the delivery of ^{18}O -depleted continental runoff from the Amazon River. The modern Amazon drainage mouth was not established until the Miocene and elevated parts of the Guyana shield prevented the development of a large river system near Demerara Rise before the Miocene (Driscoll and Diebold, 1999). Therefore, surface waters did not receive significant amounts of ^{18}O -depleted runoff in the Cenomanian. DSDP Site 144 had a Cenomanian water depth of ~ 1000 m and was probably also too far offshore (Smith et al., 1994) to have been affected substantially by low-salinity slope waters transported along the shelf edge.

The North Atlantic in the Cenomanian was connected to the Pacific through a series of >800 -m-deep straits in the Caribbean and was also connected to the South Atlantic and Tethys (Scotese and Golonka, 1992). Passages between the basins should have prevented

evaporation from making the Atlantic Basin substantially more saline than the Pacific or South Atlantic. Therefore, it is reasonable to make adjustments to our estimate of surface δ_w based upon observations of the modern zonal δ_w versus salinity relationship suggested by Zachos et al. (1994). Their equation suggests a δ_w value of -0.26‰ (relative to SMOW) for DSDP Site 144 during the Cenomanian. Coincidentally, the range of δ_w for the modern Demerara Rise encompasses the value that is estimated by the latitude versus salinity adjustment.

Recalculation of Cenomanian SSTs using a δ_w value of -0.26‰ from the latitude versus salinity adjustment yields an estimate of $34 \pm 2^\circ\text{C}$ for our averaged *H. delrioensis* data set. Our most negative $\delta^{18}\text{O}$ measurement (-4.094‰) would suggest a SST of $\sim 34 \pm 2^\circ\text{C}$. The $\pm 2^\circ\text{C}$ value results from the estimated error in the paleotemperature equation (Bice et al., 2000a), not from the precision of our isotopic measurements (which is $<0.5^\circ\text{C}$). Our estimate also allows for several degrees of uncertainty in paleolatitude for Site 144. Wallmann (2001) modeled the contribution of hydrothermal reactions to Phanerozoic δ_w and suggested that δ_w may have been 0.25‰ more negative than today in the middle Cretaceous. His model would suggest that our $33\text{--}34^\circ\text{C}$ estimates are too warm by $\sim 1^\circ\text{C}$. Our SST estimates also incorporate nearly identical estimates of δ_w , one based on the Zachos et al. (1994) equation and the other on the δ_w relationship for the modern Demerara Rise. Our paleotemperature estimates are within the model-predicted $32.5\text{--}35.0^\circ\text{C}$ estimate of seasonal temperature range for Demerara Rise by Poulsen et al. (1999).

The distinctive taphonomy demonstrated in Figure 1 is identical to that documented in claystones of late Albian age from Ocean Drilling Program (ODP) Site 1052 (Norris and Wilson, 1998; Wilson and Norris, 2001). This finding helps to confirm that clay-rich lithologies are one way to circumvent the long-running problem of finding sufficiently well preserved ancient carbonate for paleothermometric studies (Wilson and Norris, 2001). Recent study of Paleogene and Maastrichtian clay-hosted foraminifera has arrived at much the same conclusion (Pearson et al., 2001). We emphasize that chalk-hosted foraminifera continue to be useful for paleothermometry, but we are inclined to view the problem of "cool tropics" (at least in the early Late Cretaceous) as at least partly attributable to inadequacies of preservation of foraminifera in some carbonate-rich lithologies. Our data strongly suggest that the problem is not cool surface waters in the Cretaceous, but SSTs that may be several degrees warmer than today.

TROPICAL THERMOSTAT

From the perspective of atmospheric climate models, tropical SSTs warmer than the modern are not difficult to explain by elevated greenhouse gas forcing (Barron et al., 1993, 1995; Barron, 1995). However, high-latitude paleotemperature estimates are consistently underpredicted. Model "fixes" to this problem have generally increased the magnitude of poleward transport of heat through the model's slab ocean by more than four times that required for the model to produce an adequate match to modern SSTs (Barron et al., 1995; Poulsen et al., 1999; Bice and Marotzke, 2001).

How the implied high rates of heat transport would be accomplished is unclear. On one hand, the paleogeography of the early Cenozoic supports the idea of high Southern Hemisphere ocean heat transport (Bice et al., 2000b). Another possibility is that atmospheric heat transport was greater during greenhouse intervals such as the middle Cretaceous but the slab-ocean models fail to simulate this increase in latent heat transport. In any case, evidence for higher than modern tropical SSTs is necessary in order to support the hypothesis of greater latent heat transport. DSDP Site 144 data for the latest Cenomanian provide such support.

Evidence for SSTs of $33\text{--}34^\circ\text{C}$ at DSDP Site 144 argues against the hypothesis of tropical SSTs limited by one or more negative feedbacks (Graham and Barnett, 1987; Ramanathan and Collins, 1991; Waliser and Graham, 1993; Sun and Liu, 1996). In one formulation, this "thermostat hypothesis" states that, under greenhouse gas forcing, the rise of SSTs in the tropics is limited by the strong negative feedback of large-scale deep convection and resulting reflective cirrus anvil clouds (Graham and Barnett, 1987). In an analysis of the potential feedback of short-wave cloud forcing on SSTs, Ramanathan and Collins (1991) estimated that tropical SSTs would be limited to $\sim 32^\circ\text{C}$, about the lower end of our estimated temperatures. Our data suggest that the "thermostat," if there is one, might be set at least a few degrees higher than this. However, a great deal of controversy surrounds the thermostat hypothesis (e.g., Waliser, 1996). Debate concerns the relative importance of evaporation and short-wave cloud forcing, and the sign and magnitude of feedbacks among tropical sea-surface warming, the large-scale atmospheric circulation, and the wind-driven ocean currents. Although data from modern studies (such as TOGA/COARE [Tropical Ocean Global Atmosphere/Coupled Ocean Atmosphere Response Experiment]) and CEPEX (Central Equatorial Pacific Experiment) will continue to yield insight into the plausibility of a tropical thermostat in the modern system,

DSDP Site 144 data illustrate what paleoclimatology can contribute to the debate: robust evidence for tropical SSTs warmer than the modern.

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