North Atlantic warming during global cooling at the end of the Cretaceous

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ABSTRACT

Differences in regional responses to climate fluctuations are well documented on short time scales (e.g., El Niño–Southern Oscillation), but with the exception of latitudinal temperature gradients, regional patterns are seldom considered in discussions of ancient greenhouse climates. Contrary to the expectation of global warming or global cooling implicit in most treatments of climate evolution over millions of years, this paper shows that the North Atlantic warmed by as much as 6 °C (1.5‰ decrease in $\delta^{18}O$ values of planktic foraminifera) during the Maastrichtian global cooling interval. We suggest that warming was the result of the importation of heat from the South Atlantic. Decreasing North Atlantic $\delta^{18}O$ values are also associated with increasing gradients in planktic $\delta^{13}C$ values, suggesting increasing surface-water stratification and a correlated strengthening of the North Atlantic Polar Front. If correct, this conclusion predicts arctic cooling during the late Maastrichtian. Beyond implications for the Maastrichtian, these data demonstrate that climate does not behave as if there is a simple global thermostat, even on geologic time scales.

Keywords: Maastrichtian, foraminifera, stable isotopes, paleoclimate, Ocean Drilling Program, greenhouse climate.

INTRODUCTION

The extent to which low-latitude conditions affect and are affected by temporal climate patterns is a recurring question in climate and paleoclimate studies (e.g., Cane et al., 1997; Molnar and Cane, 2002; Huber and Caballero, 2003). Climate models predict that for greenhouse high latitudes to have been as warm as data indicate, the tropics should have been hotter than most data have suggested (e.g., Huber et al., 2000). This mismatch implies some combination of error in paleotemperature estimates and lack of understanding of greenhouse climate dynamics. Studies indicating that greenhouse tropics were cooler than the modern tropics (e.g., D'Hondt and Arthur, 1996) included geographically widespread sites and analyses of the best-preserved material then available. A growing data set, though, undermines conclusions regarding cool tropics. Paleotemperatures calculated from the $\delta^{18}O$ values of exquisitely well preserved tropical samples (those where recrystallization or overgrowths are demonstrably absent at the submicron scale) are 0–8 °C warmer than the modern tropics and 7–15 °C warmer than many paleotropical estimates (e.g., Pearson et al., 2001; Norris et al., 2002). These newer results suggest that a pervasive diagenetic overprint shifted all but the best-preserved tropical material toward cooler apparent temperatures. In addition to providing a potential resolution of the cool tropics paradox, by confirming model predictions about tropical temperatures, evidence for hot greenhouse tropics increases confidence in other predictions of greenhouse climate models. This study examines one of those predictions.

Model-predicted greenhouse temperatures are warmer than the control runs for the present among regions as well as across latitudes, implying that warming to or cooling from greenhouse conditions is a truly global process. However, models simulate conditions during geologic instants and have generally not been run for closely enough spaced time slices to simulate how greenhouse climates evolve on million-year time scales. Similarly, data from exquisitely preserved samples have too limited a geographic and stratigraphic coverage for analyses of them to provide empirical control on regional and/or temporal patterns of climate change. That is, neither the models nor the new tropical temperature estimates test whether different regions have congruent patterns of change. From the perspective of effects on contemporary biota and for understanding climate dynamics, regional and temporal trends are at least as important as absolute temperatures (e.g., Peters and Sloan, 2000; Poulsen et al., 2003). Fortunately, trends are more often preserved than are original values. The Maastrichtian data set contains multiple high-quality isotopic records and paleontological temperature estimates from widespread sites (Fig. 1), and is unusually well suited to test whether regionally divergent patterns are a feature of greenhouse climate evolution.

MAASTRICHTIAN CLIMATE TRENDS

The Maastrichtian (the last ~6 m.y. of the Cretaceous) was a time of widespread cooling. In addition, a brief warming pulse during the last ~0.5 m.y. of the Maastrichtian is well documented (e.g., Li and Keller, 1998; Wilf et al., 2003), and an earlier warming pulse ca. 69 Ma has been proposed (Nordt et al., 2003). Evidence for the ca. 69 Ma event has some shortcomings, including poor control on chronostratigraphy in the terrestrial section studied, lack of consistent evidence for a global warming pulse (e.g., a negative $\delta^{18}O$ excursion in benthic foraminifera from South Atlantic Hole 525A was cited as evidence for Southern Hemisphere warming, but planktic data from the same samples do not show a parallel shift; see plot reproduced in Fig. 2), large uncertainties in modeled pCO_2, and complexity related to the many factors that affect the $\delta^{18}O$ values of pedogenic calcite. Possible short-term excursions notwithstanding, diverse data demonstrate long-term Maastrichtian cooling throughout the Southern Hemisphere—as much as 6 °C in mid- to high southern latitudes and as much as 2 °C in the tropical Pacific (Fig. 1).

In the Northern Hemisphere, general cooling from a Turonian maximum (~25 m.y. earlier) through the end of the Cretaceous is well documented (e.g., Jenkyns et al., 1994; Huber et al., 2002), but Maastrichtian trends are not well established. In the North Atlantic and Tethys, various data (leaf physiognomy—Wolfe and Upchurch, 1987; $\delta^{18}O$ values of foraminifera—Corfield and Norris, 1996; Barrera and Savin, 1999; Frank and Arthur, 1999; MacLeod et al., 2000; $\delta^{18}O$ of bulk carbonate—Spicer and Corfield, 1992) hint at long-term warming. Low temporal resolution, diagenetic concerns, and the well-established evidence for Maastrichtian cooling elsewhere tend to undermine the case for North Atlantic warming. However, no counterexamples (i.e., evidence for long-term cooling in the North Atlantic or long-term warming elsewhere) have been reported.

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Geology; June 2005; v. 33; no. 6; p. 437–440; doi: 10.1130/G21466.1; 2 figures; Data Repository item 2005084.

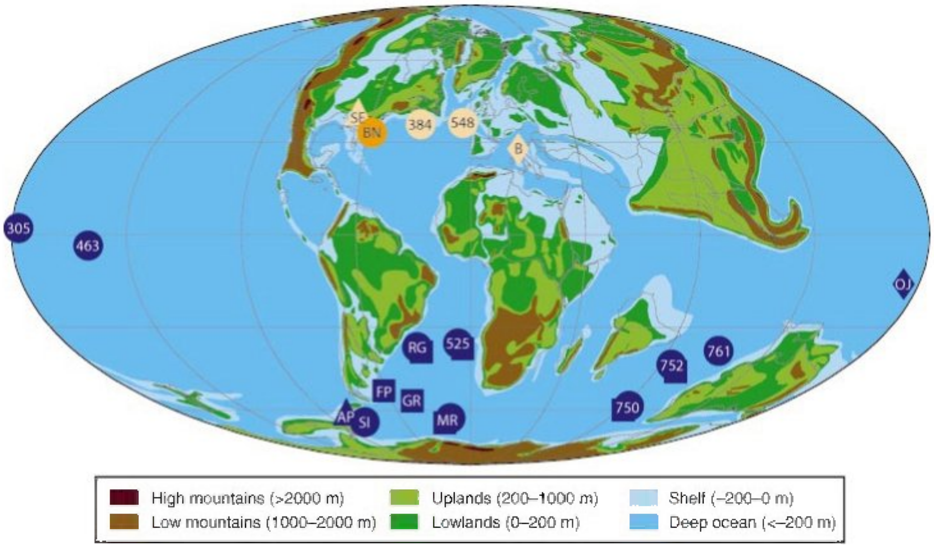

Figure 1. Maastrichtian paleogeography (Ziegler and Rowley, 1998; http://pgap.uchicago.edu/PGAPhome.html) showing approximate locations of sites with evidence for cooling (blue) or warming (orange). Dark orange circle marks Blake Nose. Except for warming pulse during last 0.5 m.y. of Maastrichtian (see text), we know of no data suggesting long-term warming outside region demarked by orange symbols or data suggesting long-term cooling within that region. Symbols: circles—δ^{18}O of foraminifera; diamonds—δ^{18}O of bulk carbonate; triangles—leaf physiognomy; squares—paleobiogeographic shifts. Localities (followed by parenthetical literature citations): AP—Antarctica Peninsula (Francis and Poole, 2002); BN—Blake Nose (Sites 390/1049, 1050, 1052) (MacLeod et al., 2000; MacLeod and Huber, 2001; this study); FP—Faukland Plateau (Sites 327, 511) (Huber and Watkins, 1992); GR—Georgia Rise (Sites 698, 700) (Huber and Watkins, 1992); OJ—Ontong Java Plateau (Sites 288, 289, 807, 1183, 1186) (MacLeod and Bergen, 2004); MR—Maud Rise (Sites 689, 690) (Huber and Watkins, 1992; Barrera and Savin, 1999); RG—Rio Grande Rise (Sites 356, 357, 516) (Huber and Watkins, 1992; Barrera and Savin, 1999; Frank and Arthur, 1999); SI—Seymour Island (benthic data only) (Barrera et al., 1987); SE—southeast United States (Wolfe and Upchurch, 1987); B—Botticione Gorge (Spicer and Corfield, 1992); numbers are Ocean Drilling Program and Deep Sea Drilling Project sites—Site 305 (Barrera and Savin, 1999), Site 384 (Corfield and Norris, 1996; Barrera and Savin, 1999), Site 463 (Barrera and Savin, 1999), Site 548 (benthic data only) (Frank and Arthur, 1999), Site 525 (Huber and Watkins, 1992; Li and Keller, 1998), Site 750 (Huber and Watkins, 1992; Barrera and Savin, 1999; MacLeod and Huber, 1996), Site 752 (Seto et al., 1991; Huber and Watkins, 1992), and Site 761 (MacLeod and Huber, 1996; Barrera and Savin, 1999).

MATERIALS AND METHODS

To determine Maastrichtian climate trends in the North Atlantic more rigorously, we examined δ^{18}O and δ^{13}C values in three Ocean Drilling Program (ODP) and Deep Sea Drilling Project (DSDP) sites on Blake Nose (ODP Site 390-DSDP Site 1049, DSDP Sites 1050 and 1052; Fig. 1). Because a hiatus limits its potential resolution at Site 390-1049, we concentrated on Sites 1050 and 1052. We analyzed ~300 new samples (not including replicates), increasing the stratigraphic and taxonomic database for this area by about five times. Coring gaps and slumping are a problem at Sites 1050 and 1052 (MacLeod et al., 2003), but a new age model incorporating Sr isotopic data (see GSA Data Repository[1]) demonstrates that the samples available from Blake Nose provide better than million-year resolution throughout the Maastrichtian (i.e., we can distinguish between the relatively brief warming pulses discussed here and trends spanning millions of years).

Samples were processed by using standard procedures. Oxygen and carbon isotopic ratios of fine fraction carbonate (<63 μm) and size-sorted specimens of selected foraminifera free of adhering matrix were measured on a Kiel III carbonate device–ThermoFinnigan DeltaPlus isotope ratio mass spectrometer. Results are reported in standard δ notation relative to the Vienna Peedee belemnite standard. External precision of <0.02‰ and <0.06‰ for δ^{13}C and δ^{18}O (1σ standard deviation) is estimated from results for the NBS-19 standard run concurrently. Preservation in these samples is generally very good to excellent (D'Hondt and Arthur, 1996; MacLeod et al., 2001; Rudnicki et al., 2001); many foraminiferal tests preserve primary shell microstructure and are translucent. Scanning electron microscope images show micron-scale recrystallization, but this degree of recrystallization should not compromise our analysis; we are concerned with the direction of primary isotopic trends through the sections, not with the precise initial values, and the availability of correlative samples from three sites representing different burial histories allows possible diagenetic artifacts to be evaluated.

RESULTS

At all three sites, planktic δ^{18}O values decrease by 0.5‰–1.5‰ between 71 and 66 Ma—a change that is similar in magnitude to, but opposite in direction from, trends in many Southern Hemisphere sites (Fig. 2; Data Repository Tables DR1–DR3 [see footnote one]). Stratigraphic resolution is limited at Site 390, but at Sites 1050 and 1052, the decrease is gradual over a stratigraphic interval representing several million years. Over the same interval, within-sample planktic δ^{13}C gradients increase from ~1‰ to ~2‰. A short-term excursion ca. 65.5 Ma that is superimposed on the long-term negative trend in δ^{18}O is most obvious in the benthic data for Hole 1050C (Fig. 2).

DISCUSSION

If primary, the ~1.5‰ decrease in planktic δ^{18}O values suggests as much as 6 °C of surface warming or a 3–5 ppt salinity decrease across the Maastrichtian (MacLeod and Huber, 1996). Distinguishing between temperature and seawater evaporation and/or dilution effects on measured δ^{18}O values is not easy, but potential diagenetic concerns can be empirically addressed.

Potential Artifacts

The timing and magnitude of the short-term, negative δ^{18}O excursion to benthic values of ~−0.5‰ at 65.5 Ma (Fig. 2) likely represent the well-documented, globally recognized pulse of warming (e.g., Li and Keller, 1998; Wilf et al., 2003, and references therein). Preservation of this excursion demonstrates that diagenesis has not obscured primary foraminiferal δ^{18}O trends on Blake Nose. We think that diagenesis has preferentially lowered δ^{18}O values in the oldest samples from Hole 1052E. These samples contain foraminifera with only good preservation and with δ^{18}O values almost I‰ lower than values in correlative samples at the other two sites. A negative diagenetic overprint is expected with deep burial. However, because it lowers δ^{18}O values in older (more deeply buried) samples, the shift toward lower values we see in younger (less deeply buried) samples at each site is not explained by this process.

Early diagenetic alteration also fails to explain the observed trends. Although diagenesis in relatively cool bottom waters or near-

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[1] GSA Data Repository item 2005084, age model (including tables and figures) and Tables DR1–DR3, is available online at www.geosociety.org/pubs/ft2005.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

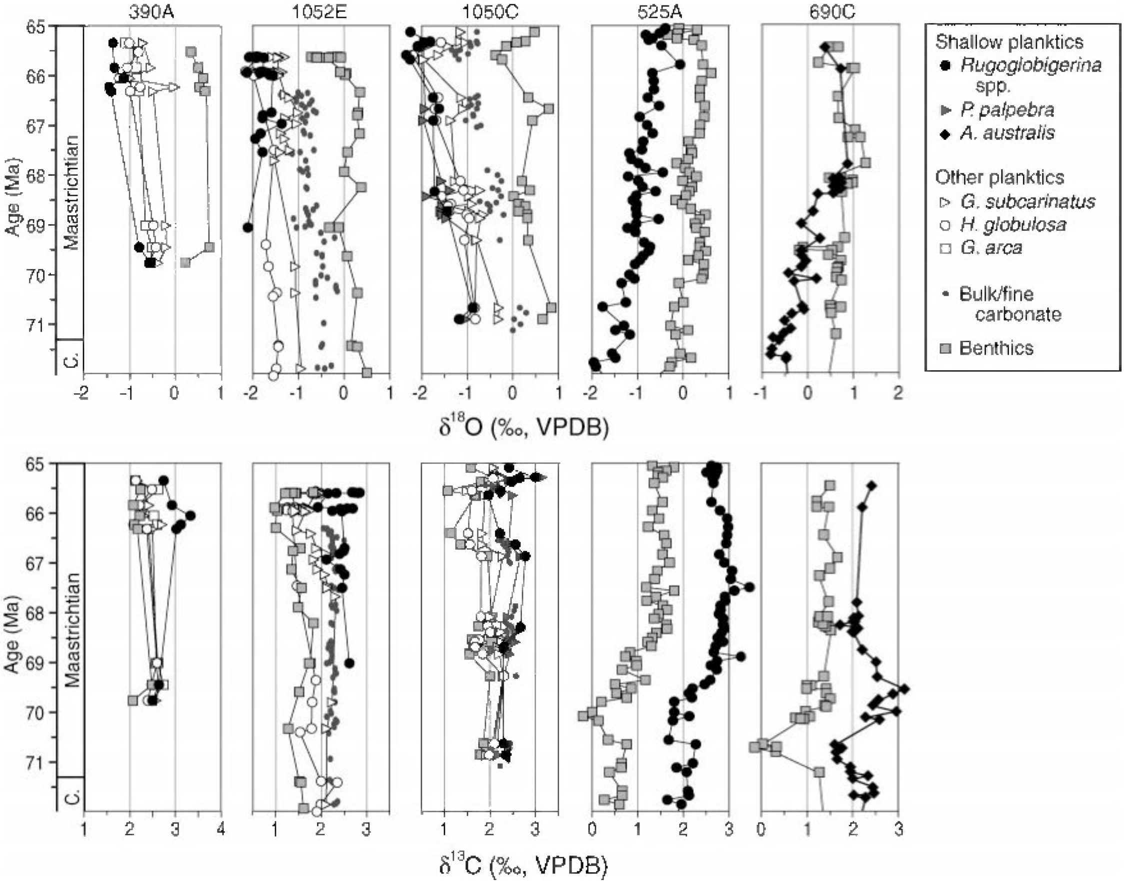

Figure 2. Stable isotopic data for three Blake Nose sites, Deep Sea Drilling Project Site 525 (35°S paleolatitude), and Ocean Drilling Program Site 690 (Maud Rise, 65°S paleolatitude) plotted against age. Planktic taxa from Blake Nose all show 0.5‰–1.5‰ decrease in δ^{18}O values across Maastrichtian, suggesting warming of subtropical western North Atlantic during last 5–6 m.y. of Cretaceous. C—Campanian; VPDB—Vienna Peedee belemnite standard. Blake Nose isotopic data and description of age model are presented in GSA Data Repository (see text footnote one). Data for Hole 525A are from Li and Keller (1998) with age model after Wilf et al. (2003). Data and age model for Hole 690C are from Barrera and Savin (1999).

bottom pore waters could create a cool bias in paleotropical temperature estimates (e.g., Schrag et al., 1995; Pearson et al., 2001), the three Blake Nose sites were as far north of the equator during the Maastrichtian as Site 525 and the Rio Grande Rise sites were south (Fig. 1). Data for Site 525 are representative of the South Atlantic; they show similar benthic values and the same range of planktic δ^{18}O values, but the temporal trends in planktic δ^{18}O values are opposite of those seen at Blake Nose (Fig. 2). Further, to cause a decrease in δ^{18}O upsection, either the extent of the early diagenetic alteration would have had to decrease consistently at the three Blake Nose sites or bottom-water–pore-water temperatures would have had to rise through time. If anything, though, benthic δ^{18}O curves at the Blake Nose suggest slight cooling of local bottom waters from 69 to 66 Ma when planktic values suggest warming, and the three sites represent different water depths and different burial depths (i.e., different diagenetic histories). Thus, we are confident that the observed pattern of decreasing planktic δ^{18}O values upsection at Blake Nose is a reliable paleoenvironmental signal.

North Atlantic Stratification

Correlative with decreasing planktic δ^{18}O values, the local water column became increasingly stratified. Increased stratification is demonstrated particularly well by the increase in the within-sample δ^{13}C gradient from ~1‰ at 70 Ma to ~2‰ at 66 Ma (Fig. 2), and is apparent in the δ^{18}O data from Hole 1050C. Increasing stratification is also supported by diversification among planktic foraminifera from the early to the late Maastrichtian in Hole 390A (MacLeod et al., 2000). It seems unlikely that consistent signals in three different data types (δ^{13}C, δ^{18}O, and foraminiferal diversity) would all be artifacts.

Maastrichtian Paleoceanography

The magnitudes of the δ^{18}O and δ^{13}C signals observed indicate a significant paleoceanographic modification of the North Atlantic during the Maastrichtian, and this modification occurs over several million years. Biostratigraphy, magnetostratigraphy, and chemostratigraphy (age model; see footnote one) demonstrate that there are samples from 1050C and 1052E that fall both on the warming trend proposed herein and between the warming pulse in the last ~0.5 m.y. of the Maastrichtian (e.g., Li and Keller, 1998; Wilf et al., 2003) and the proposed 69 Ma warming pulse (Nordt et al., 2003).

Previous studies have suggested that the North Atlantic became an intermediate or deep-water source during the Maastrichtian (e.g., Frank and Arthur, 1999; D'Hondt and Arthur, 2002), and if subsurface waters exported from the North Atlantic were replaced by surface waters flowing north from the South Atlantic, the resulting heat piracy would explain divergent δ^{18}O trends between the two Atlantic basins (e.g., Crowley and North, 1991; Seidov and Maslin, 2001; Fig. 2). That warming is the dominant cause of planktic δ^{18}O trends observed at Blake Nose is consistent with leaf data from the southeast United States (Wolfe and Upchurch, 1987), with the distance to the Cretaceous shoreline making a freshwater cap an unlikely possibility (MacLeod et al., 2001), and with the presence of taxonomically similar, diverse foraminiferal assemblages throughout the Maastrichtian implying normal marine conditions (MacLeod et al., 2000, 2001). The lack of a big change in North Atlantic salinity is more a prediction of this study than it is a conclusion constrained by data.

A second prediction of our analysis is cooling in the Maastrichtian arctic. Increased stratification of the Blake Nose water column suggests a more strongly developed thermocline, which would result from an intensification of the North Atlantic polar front. This conclusion is supported by many single-specimen analyses from Hole 1050C (Isaza et al., 2004). A stronger polar front might also reduce oceanic and atmospheric heat transport into the arctic, leading to arctic cooling and reinforcing North Atlantic downwelling. If suitable Maastrichtian arctic sections can be sampled, the prediction of cooling should be easily testable.

CONCLUSIONS

Factors operating at the scale of ocean basins and over geologic time led to large regional differences in the expression of Late Cretaceous global cooling. In the North Atlantic, the regional expression of the Maastrichtian cooling trend was decreasing $\delta^{18}O$ values (apparent warming) and increased water-column stratification. We suggest that an importation of heat from the South Atlantic and a strengthening of the North Atlantic polar front explain these results and predict correlative cooling in the arctic. Such regional differences are clearly important in decadal-scale climate fluctuations today and should be considered in studies of ancient greenhouse climates as well.

ACKNOWLEDGMENTS

We thank K. Bice, T. Frank, M. Huber, and C. Kelley for comments on early drafts of this paper and T. Frank for sharing data. Samples were provided by the Ocean Drilling Program, which is sponsored by the U.S. National Science Foundation and participating countries under management of Joint Oceanographic Institutions, Inc. Funding was provided by the U.S. Science Support Program, U.S. National Science Foundation, and Smithsonian Scholarly Studies Program.

REFERENCES CITED

Barrera, E., and Savin, S.M., 1999, Evolution of late Campanian–Maastrichtian marine climates and oceans, *in* Barrera, E., and Johnson, C., eds., Evolution of the Cretaceous ocean-climate system: Geological Society of America Special Paper 332, p. 245–282.

Barrera, E., Huber, B.T., Savin, S.M., and Webb, P.N., 1987, Antarctic marine temperatures: Late Campanian through early Paleocene: Paleoceanography, v. 2, p. 21–47.

Cane, M.A., Clement, A.C., Kaplan, A., Kushnir, Y., Pozdnyakov, D., Seager, R., Zebiak, S.E., and Murtugudde, R., 1997, Twentieth-century sea surface temperature trends: Science, v. 275, p. 957–960.

Corfield, R.M., and Norris, R.D., 1996, Deep water circulation in the Paleocene ocean, *in* Knox, R.O., et al., eds., Correlation of the early Paleogene in northwest Europe: Geological Society [London], p. 443–456.

Crowley, T.J., and North, G.R., 1991, Paleoclimatology: New York, Oxford University Press, 339 p.

D'Hondt, S., and Arthur, M.A., 1996, Late Cretaceous oceans and the cool tropic paradox: Science, v. 271, p. 1838–1841.

D'Hondt, S., and Arthur, M.A., 2002, Deep water in the late Maastrichtian ocean: Paleoceanography, v. 17, p. 8-1–8-11.

Francis, J.E., and Poole, I., 2002, Cretaceous and early Tertiary climates of Antarctica: Evidence from fossil wood: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 182, p. 47–64.

Frank, T.D., and Arthur, M.A., 1999, Tectonic forcing of Maastrichtian ocean-climate evolution: Paleoceanography, v. 14, p. 103–119.

Huber, B.T., and Watkins, D.K., 1992, Biogeography of Campanian-Maastrichtian calcareous plankton in the region of the Southern Ocean: Paleogeographic and paleoclimatic implications, *in* Kennett, J.P., and Warnke, D.A., eds., The Antarctic paleoenvironment: A perspective on global change: American Geophysical Union Antarctic Research Series, v. 56, p. 31–60.

Huber, B.T., MacLeod, K.G., and Wing, S.L., eds., 2000, Warm climates in Earth history: London, Cambridge University Press, 462 p.

Huber, B.T., Norris, R.D., and MacLeod, K.G., 2002, Deep sea paleotemperature record of extreme warmth during the Cretaceous Period: Geology, v. 30, p. 123–126.

Huber, M., and Caballero, R., 2003, Eocene El Niño: Evidence for robust tropical dynamics in the "hothouse": Science, v. 299, p. 877–881.

Isaza, C., MacLeod, K.G., and Huber, B.T., 2004, Vertical isotopic gradients among foraminifera and evolution of the Maastrichtian North Atlantic thermocline: Geological Society of America Abstracts with Programs, v. 36, p. 17.

Jenkyns, H.C., Gale, A.S., and Corfield, R.M., 1994, Carbon- and oxygen-isotope stratigraphy of the English Chalk and the Italian Scaglia and its palaeoclimatic significance: Geological Magazine, v. 131, p. 1–34.

Li, L., and Keller, G., 1998, Maastrichtian climate, productivity and faunal turnovers in planktic foraminifera in South Atlantic DSDP Sites 525A and 21: Marine Micropaleontology, v. 33, p. 55–86.

MacLeod, K.G., and Bergen, J.A., 2004, Apparent cooling in the tropical Pacific during the Maastrichtian and diagenetic artifacts in Late Cretaceous stable isotopic trends in bulk carbonate from Ontong Java plateau, *in* Mahoney, J.J., et al., Proceedings of the Ocean Drilling Program, Scientific results, Volume 192: College Station, Texas, Ocean Drilling Program, p. 1–15 (CD-ROM).

MacLeod, K.G., and Huber, B.T., 1996, Reorganization of deep ocean circulation accompanying a Late Cretaceous extinction event: Nature, v. 380, p. 422–425.

MacLeod, K.G., and Huber, B.T., 2001, The Maastrichtian record at Blake Nose (western North Atlantic) and implications for global palaeoceanographic and biotic changes, *in* Kroon, R., et al., eds., Western North Atlantic Palaeogene and Cretaceous palaeoceanography: Geological Society [London] Special Publication 183, p. 111–130.

MacLeod, K.G., Huber, B.T., and Ducharme, M.L., 2000, Paleontological and geochemical constraints on changes in the deep ocean during the Cretaceous greenhouse interval, *in* Huber, B.T., et al., eds., Warm climates in Earth history: Cambridge, Cambridge University Press, p. 241–274.

MacLeod, K.G., Huber, B.T., Pletsch, T., Röhl, U., and Kucera, M., 2001, Maastrichtian foraminiferal and paleoceanographic changes on Milankovitch time scales: Paleoceanography, v. 16, p. 133–154.

MacLeod, K.G., Huber, B.T., and Fullagar, P.D., 2003, $^{87}Sr/^{86}Sr$ test of the degree of impact induced slope failure in the Maastrichtian of the western North Atlantic: Geology, v. 31, p. 311–314.

Molnar, P., and Cane, M.A., 2002, El Niño's tropical and teleconnections as a blueprint for pre–Ice Age climate: Paleoceanography, v. 17, p. 11-1–11-12.

Nordt, L., Atchley, S., and Dworkin, S., 2003, Terrestrial evidence for two greenhouse events in the latest Cretaceous: GSA Today, v. 13, no. 12, p. 4–9.

Norris, R.D., Bice, K.L., Magno, E.A., and Wilson, P.A., 2002, Jiggling the tropical thermostat in the Cretaceous hothouse: Geology, v. 30, p. 299–302.

Pearson, P.N., Ditchfield, P.W., Singano, J., Harcourt-Brown, K.G., Nicholas, C.J., Olsson, R.K., Shackleton, N.J., and Hall, M.A., 2001, Warm tropical sea surface temperatures in the Late Cretaceous and Eocene epochs: Nature, v. 413, p. 481–487.

Peters, R.B., and Sloan, L.C., 2000, High concentrations of greenhouse gases and polar stratospheric clouds: A possible solution to high-latitude faunal migration at the latest Paleocene thermal maximum: Geology, v. 28, p. 979–982.

Poulsen, C., Gendaszek, A., and Jacob, R., 2003, Did the rifting of the Atlantic Ocean cause the Cretaceous thermal maximum?: Geology, v. 31, p. 115–118.

Rudnicki, M.D., Wilson, P.A., and Anderson, W.T., 2001, Numerical models of diagenesis, sediment properties, and pore fluid chemistry on a paleoceanographic transect: Blake Nose, Ocean Drilling Program Leg 171B: Paleoceanography, v. 16, p. 563–575.

Schrag, D.P., DePaolo, D.J., and Richter, F.M., 1995, Reconstructing past sea surface temperatures: Correcting for diagenesis of bulk marine carbonate: Geochimica et Cosmochimica Acta, v. 59, p. 2265–2278.

Seidov, D., and Maslin, M., 2001, Atlantic Ocean heat piracy and the bipolar climate see-saw during Heinrich and Dansgaard-Oescher events: Journal of Quaternary Science, v. 16, p. 321–328.

Seto, K., Nomura, R., and Niitsuma, N., 1991, Data report: Oxygen and carbon isotope records of the upper Maastrichtian to lower Eocene benthic foraminifers at Site 752 in the eastern Indian Ocean, *in* Weissel, J., et al., Proceedings of the Ocean Drilling Program, Scientific results, Volume 121: College Station, Texas, Ocean Drilling Program, p. 885–889.

Spicer, R.A., and Corfield, R.M., 1992, A review of terrestrial and marine climates in the Cretaceous with implications for modeling the "Greenhouse Earth": Geological Magazine, v. 129, p. 169–180.

Wilf, P., Johnson, K.R., and Huber, B.T., 2003, Correlated terrestrial and marine evidence for global climate changes before mass extinction at the Cretaceous-Paleogene boundary: National Academy of Sciences Proceedings, v. 100, p. 599–604.

Wolfe, J.A., and Upchurch, G.R., Jr., 1987, North American nonmarine climates and vegetation during the Late Cretaceous: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 61, p. 33–77.

Ziegler, A.M., and Rowley, D.B., 1998, The vanishing record of epeiric seas with emphasis on the Late Cretaceous "Hudson Seaway," *in* Crowley, T.J., and Burke, K., eds., Tectonic boundary conditions for climate reconstructions: Oxford, Oxford University Press, p. 147–165.

Manuscript received 14 December 2004
Revised manuscript received 8 February 2005
Manuscript accepted 10 February 2005

Printed in USA