

Late Quaternary climate change from $\delta^{18}\text{O}$ records of multiple species of planktonic foraminifera: High-resolution records from the anoxic Cariaco Basin, Venezuela

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Abstract. Seasonal trade wind-induced upwelling along the southern margin of the Caribbean Sea occurs in response to the annual migration of the Intertropical Convergence Zone. Laminated, high deposition rate sediments of the Cariaco Basin, a small anoxic basin on the Venezuelan continental shelf, clearly record large changes in the past intensity of this upwelling. Because sediments of the Cariaco Basin are largely unbioturbated, they offer a natural opportunity to study the stable isotopic records of multiple planktonic foraminiferal taxa and to evaluate their sensitivity to both the modern hydrography and temporal changes in upwelling intensity and climate. Oxygen isotope data ($\delta^{18}\text{O}$) from four dominant foraminiferal taxa are presented for the time period covering the last 28 kyr. The $\delta^{18}\text{O}$ data from *Globigerina bulloides*, after correction for nonequilibrium precipitation, are used as a monitor of sea surface conditions during the winter-spring upwelling season. The $\delta^{18}\text{O}$ data from white *Globigerinoides ruber* are used as a measure of annual-average conditions in the near surface, while pink *G. ruber* data are consistent with use as an index of end-member conditions during the summer-fall nonupwelling season. Data from the deeper dwelling *Neogloboquadrina dutertrei* yield information on conditions near the base of the local thermocline. During the last glacial, $\delta^{18}\text{O}$ data from *G. ruber* and generally reduced interspecific differences indicate cooling of surface waters over the Cariaco Basin by up to 4°C. This longer-term cooling does not appear to be related to changes in upwelling intensity along the coast but may instead reflect more regional cooling of the larger Caribbean. Superimposed on this pattern, between 12.6 and ~10 ka, is a convergence of $\delta^{18}\text{O}$ data between *G. bulloides* and *N. dutertrei*, implying much stronger upwelling during the last deglaciation. This scenario is consistent with other evidence for high productivity at this time. At ~14 ka, a sharp $\delta^{18}\text{O}$ depletion event observed in all taxa seems to have been produced by increased freshwater discharge to the southern Caribbean, suggesting either higher regional rainfall or the influence of glacial melting in the Andes. Minimum $\delta^{18}\text{O}$ values of pink *G. ruber* around 6-7 ka record warmer summer sea surface temperatures and/or decreased salinity in the mid-Holocene.

Introduction

The Cariaco Basin is a small, deep structural depression located on the northern continental shelf of Venezuela. Largely isolated from the open Caribbean Sea by a series of shallow sills, the Cariaco Basin is presently anoxic below a depth of about 300 m because of restricted water exchange with the open Caribbean and

oxygen demand created by highly productive conditions associated with intrabasinal seasonal upwelling. Since the work by Heezen *et al.* [1958, 1959], it has been known that laminated sediments which accumulate here are nearly undisturbed by bioturbation, exhibit high deposition rates (30 to >100 cm/kyr), and contain well-preserved assemblages of both calcareous and siliceous microfossils. Thus all requirements are present for high-resolution paleoceanographic reconstructions. Previous microfossil studies have focused primarily on reconstruction of late Quaternary paleoenvironmental conditions using planktonic foraminifera [Kipp and Towner, 1975; Overpeck *et al.*, 1989; Peterson *et al.*, 1991]. Here we present the first stable isotope records of foraminiferal $\delta^{18}\text{O}$ derived from species with differing seasonal and depth preferences to explore their potential for reconstructing detailed hydrographic scenarios for the late Quaternary.

Numerous studies have utilized $\delta^{18}\text{O}$ data from multiple species of planktonic foraminifera to reconstruct variations in water column structure and the seasonal range of sea surface temperatures (SST) through time [e.g., Emiliani, 1954; Fairbanks *et al.*, 1982; Curry *et al.*, 1983; Deuser and Ross, 1989; Ravelo *et al.*, 1990; Ravelo and Fairbanks, 1992]. Such studies are usually hampered because most marine sediments are bioturbated, resulting in mixing of specimens

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of various ages and alteration of original signals. In the Cariaco Basin, high sedimentation rates and bioturbation that is greatly reduced, if not largely absent, result in a dramatic limit to mixing and minimizes the time span of discrete sediment samples. We present $\delta^{18}\text{O}$ data from four foraminiferal taxa, *Globigerina bulloides*, *Neogloboquadrina dutertrei*, and the white and pink morphotypes of *Globigerinoides ruber*, that constitute a major fraction of the faunal assemblage in the Cariaco Basin [Peterson et al., 1991]. These data are used to examine paleoenvironmental changes over a time interval (0-28 ka) that encompasses the last glacial, the deglaciation, and the Holocene.

Seasonal Hydrography and Biology

As a result of seasonal changes in the position of the Intertropical Convergence Zone (ITCZ) in the tropical Atlantic, the patterns of upwelling and precipitation along the southern Caribbean margin are markedly skewed [Wüst, 1964; Hastenrath, 1978; Muller-Karger and Aparicio-Castro, 1994]. Between the months of January and about March, when the ITCZ is south of the equator, strong trade winds blowing along the coast of Venezuela result in Ekman drift-induced upwelling of cool, nutrient-rich waters. At this time of year, gross primary production rates along the coast are up to 20 times greater than those found in the open Caribbean to the north [Curl, 1960]. Regionally, the upwelling season corresponds to the dry season since the ITCZ, with its attendant rainfall, lies far to the south. Beginning in about June or July, as the ITCZ moves north to a position near the Venezuelan coast, the trade winds diminish, and the upwelling weakens or is largely shut off. This northward migration of the ITCZ triggers the local rainy season which results in increased fluvial discharge from rivers that influence the southern Caribbean region.

The pronounced seasonal changes in the surface hydrography along the north coast of Venezuela give rise to a systematic turnover in the local biology. In particular, near-surface plankton tows made in the Cariaco Basin by Miro [1971] provide important data on

seasonal changes in the local foraminiferal fauna that form the basis of our selection of taxa for isotopic study. During January and February, when upwelling over the basin is most intense, Miro found an initial bloom of phytoplankton (mainly diatoms) to be closely followed by a nearly monospecific fauna dominated by *G. bulloides*. Foraminiferal standing stock was at a maximum and faunal diversity at a minimum at this time. *G. bulloides*, typically a subpolar species [e.g., Bé and Tolderlund, 1971; Kipp, 1976], adheres to this relationship in upwelling environments elsewhere in the tropics [e.g., Duplessy et al., 1981; Prell and Curry, 1981; Ganssen and Sarnthein, 1983; Prell, 1984a, b; Reynolds and Thunell, 1985]. In a study of sediment trap material from the San Pedro Basin off California, Sautter and Thunell [1991] found that the $\delta^{18}\text{O}$ of *G. bulloides* accurately records SST during periods of upwelling, a premise that we adopt in this work.

During the nonupwelling season (summer and fall), conditions of minimum standing stock in the Cariaco Basin coincide with a more diverse assemblage dominated by the shallow-dwelling warm water taxon *G. ruber*, while *G. bulloides* is absent [Miro, 1971]. Miro did not distinguish between the white and pink pigmented morphotypes of *G. ruber*, but we have chosen to consider them separately because they tend to have distinct biogeographies in the tropical Atlantic [Kipp, 1976] and their downcore abundances vary independently of one another in the Cariaco Basin [Peterson et al., 1991]. Data from plankton tow studies indicate that pink *G. ruber* lives only during the warmer summer months, while the white variety is found year round in surface waters of the tropical Atlantic [e.g., Tolderlund and Bé, 1971; Deuser and Ross, 1989].

N. dutertrei is generally thought to be a deeper dweller than other taxa considered here. A number of studies document that *N. dutertrei* seems to have $\delta^{18}\text{O}$ compositions that reflect calcification at relatively constant temperatures at depth in the water column [e.g., Curry and Matthews, 1981; Fairbanks et al., 1980, 1982; Curry et al., 1983]. Thus, stratigraphic variations in this species $\delta^{18}\text{O}$ may provide a measure of ice volume and/or local evaporation/precipitation effects.

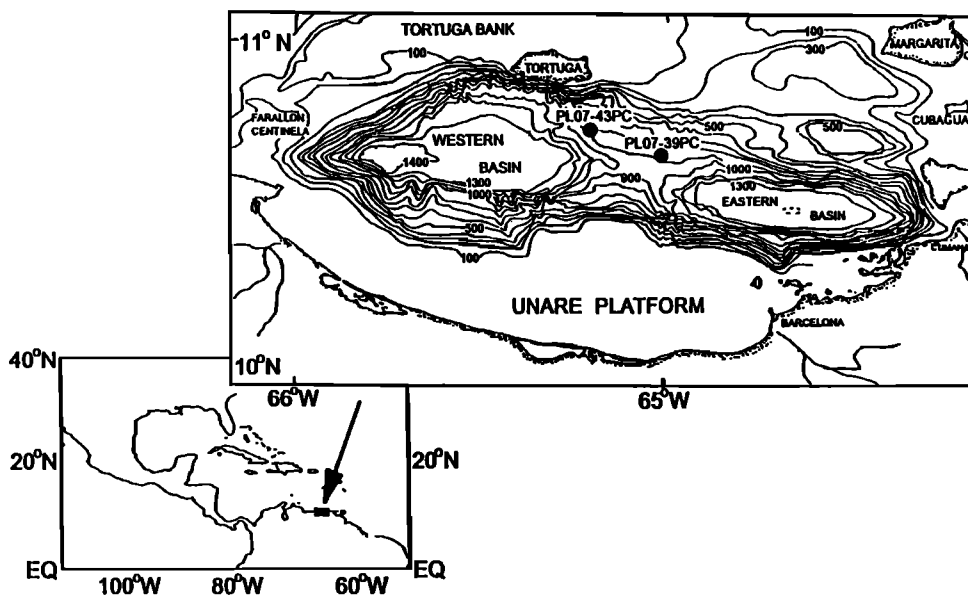


Figure 1. Location map and bathymetry (in meters) of Cariaco Basin showing position of the two PLUME-07 piston cores utilized in this study.

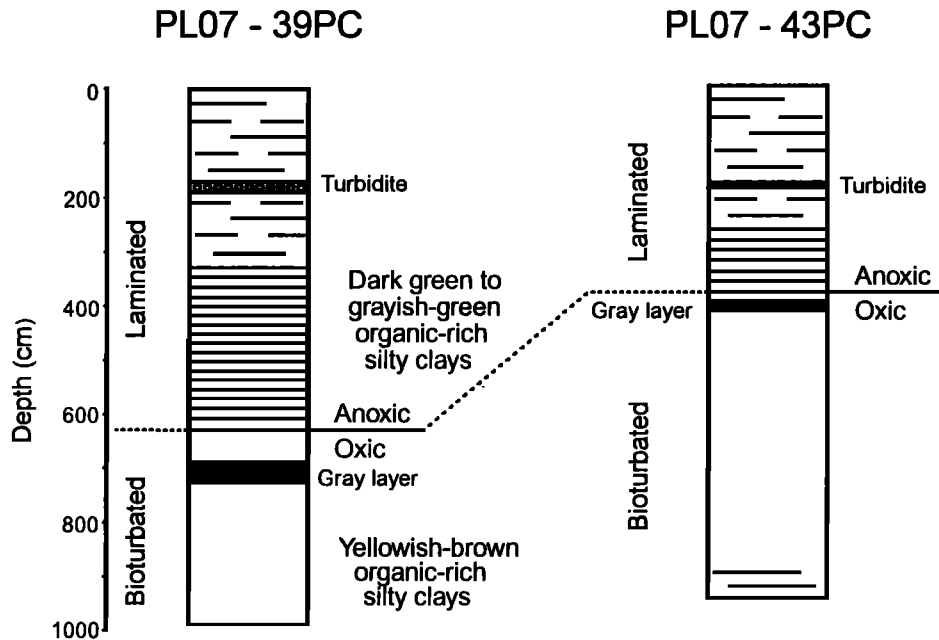


Figure 2. Generalized lithologies of cores PL07-39PC and PL07-43PC from the Cariaco Basin. Two distinct lithologic units can be identified: an upper laminated unit deposited under anoxic depositional conditions, and a lower, weakly bioturbated unit deposited under formerly oxic conditions. Sediments are much more distinctly laminated in the lower portion of the upper anoxic unit. Laminae reappear at the base of core PL07-43PC, suggesting an earlier phase of anoxic conditions.

Materials and Methods

Samples from two piston cores collected in the Cariaco Basin during Leg 7 of the PLUME Expedition (R/V *Thomas Washington*) are utilized in this study (Figure 1). Piston core PL07-39PC, 993 cm in length, was recovered from the eastern side of the central basin high at a water depth of 790 m ($10^{\circ}42.00'N$, $64^{\circ}56.50'W$). Core PL07-43PC, 948 cm in length, was recovered from a water depth of 819 m on the western side of the same feature at $10^{\circ}44.80'N$, $65^{\circ}11.30'W$. Lithologies are like those found in undisturbed sequences throughout the basin [Needham, 1971; Athearn, 1965; Peterson *et al.*, 1991], with two distinct sediment units that can be identified (Figure 2). An upper unit, 0-627 cm in PL07-39PC and 0-372 cm in PL07-43PC, consists primarily of grayish-green, laminated silty clays. Within this unit, the lower portion is much more distinctly laminated and generally lighter in color. Deposition of the upper unit occurred under fully anoxic conditions as indicated by the undisturbed laminae and absence of benthic foraminifera, ostracods, and micromolluscs. Microscopic examination of the light-dark laminae couplets and radiometric analyses have shown that paired laminae in the Cariaco Basin sediments accurately reflect seasonal contrasts in deposition and are true varves [Hughen *et al.*, 1996a, b].

Sediments of the lower unit in both cores consist of yellowish-brown, nonlaminated, silty clays that accumulated under oxic bottom conditions. Benthic foraminifera are present, but the impoverished nature of the fauna indicates low oxygen levels and a restricted circulation. Within this unit, a distinct gray mottled layer is observed between 685 and 725 cm in PL07-39PC and between 390 and 420 cm in PL07-43PC (Figure 2). Near the very base of PL07-43PC, laminated sediments reappear, implying an earlier phase of anoxic deposition.

A chronology for events in the two cores comes from a series of accelerator mass spectrometer (AMS) ^{14}C dates generated on monospecific samples of *G. bulloides* ($>150 \mu m$) at the Lawrence Livermore National Laboratory (Table 1). Our age model for PL07-39PC comes from a series of 29 AMS dates distributed along the length of the core, while PL07-43PC has 5 AMS dates from its thicker lower unit (Figure 3). To correct for the radiocarbon differences between the local surface waters and atmosphere, 420 years were first subtracted from the measured radiocarbon age of each dated sample. This reservoir correction for the Cariaco Basin was calculated using ^{14}C dates on near-surface box core sediments that have been independently dated using ^{210}Pb and varve counts [Hughen *et al.*, 1996b].

The detailed AMS ^{14}C chronology in PL07-39PC indicates relatively linear sedimentation rates over long intervals of time, with the highest rates associated with the period of deglaciation. Over the last 10 kyrs or so, bulk sedimentation rates averaged just over 30 cm/kyr. During this interval of time, deposition of the more faintly laminated portion of the unit occurred. Sedimentation rates jump sharply below this zone to >100 cm/kyr at the level where laminae become thicker and more distinct, remain relatively high down into the glacial section of the core, and then drop again in sediments older than about 15 ka.

In the three samples dated between 400 and 500 cm in PL07-39PC, a "plateau" in ^{14}C ages is observed (Table 1 and Figure 3) with each level yielding dates of around 10,000 radiocarbon years. This phenomenon of relatively constant radiocarbon dates at about 10 ka is well known from other records [e.g., Oeschger *et al.*, 1980; Bard *et al.*, 1990; Becker *et al.*, 1991] and is probably related to changes in ^{14}C production rate that have not yet been fully constrained by varve and dendrochronological studies. A similar pattern of nearly identical ^{14}C ages is observed in samples from the 723 and

Table 1. Radiocarbon Ages for Cariaco Basin Sediment Samples

Sample ID	Depth, cm	¹⁴ C Age, ka	CAMS #
39PC/6-8	6-8	860 (±80)	1729
39PC/25-7	25-27	1,400 (±70)	1730
39PC/44-6	44-46	1,840 (±70)	1731
39PC/73-6	73-76	2,580 (±80)	1732
39PC/103-5	103-105	3,500 (±100)	1733
39PC/118-22	118-122	4,340 (±70)	2951
39PC/143-5	143-145	4,940 (±70)	1734
39PC/163-7	163-167	5,980 (±60)	2952
39PC/183-6 *	183-186	10,630 (±160)	1747
39PC/212-7	212-217	7,360 (±60)	2953
39PC/223-5	223-225	7,580 (±70)	1735
39PC/253-5	253-255	8,850 (±90)	1736
39PC/293-5	293-295	9,700 (±80)	1737
39PC/305-9	305-309	9,990 (±60)	2954
39PC/334-6	334-336	10,070 (±100)	1738
39PC/401-4	401-404	10,730 (±120)	1739
39PC/441-4	441-444	10,760 (±80)	2955
39PC/462-5	462-465	10,690 (±80)	1740
39PC/521-4	521-524	11,430 (±150)	1741
39PC/573-6	573-576	12,380 (±100)	1742
39PC/621-2.5	621-622.5	13,020 (±220)	1748
39PC/622.5-5.5	622.5-625.5	13,390 (±200)	1749
39PC/632-6	632-636	14,530 (±310)	1750
39PC/641-3	641-643	14,410 (±260)	2956
39PC/723-4	723-724	13,960 (±300)	1751
39PC/750-3	750-753	13,930 (±100)	1743
39PC/770-3	770-773	14,780 (±140)	1744
39PC/902-5	902-905	17,600 (±150)	1745
39PC/982-3	982-983	21,210 (±210)	1746
43PC/364-8	364-368	12,710 (±110)	1752
43PC/552-6	552-556	16,370 (±140)	1753
43PC/674-8	674-678	20,460 (±200)	1754
43PC/834-8	834-838	25,220 (±330)	1755
43PC/933-7	933-937	28,350 (±390)	1756

All AMS ¹⁴C analyses are based on monospecific samples of *Globigerina bulloides* and were performed at the Center for Accelerator Mass Spectrometry (CAMS), Lawrence Livermore National Laboratory. Listed ages are in radiocarbon years using the conventional Libby half-life of 5568 years, with ¹⁴C errors reported at ±1σ. Ages quoted in the text have been reservoir corrected by subtracting 420 years from each measured date

* Turbidite sample.

750 cm levels, with each giving a date of ~13,500 radiocarbon years. These two samples fall at the approximate level of the distinctive gray layer noted earlier and may be related to rapid deposition of this stratigraphic interval. Above the gray layer and just below the oxic-anoxic transition, two samples give somewhat older ¹⁴C ages. There is no visual evidence of core disturbance at this level, and we currently have no explanation for this unusual distribution of dates. Efforts are underway to replicate dates in this interval from other nearby cores. Higher up in the stratigraphic sequence of PL07-39PC, the AMS ¹⁴C date at 185 cm clearly confirms the presence of a turbidite (Figure 2) that we have subtracted out of the sedimentary sequence. This turbidite appears to correlate with a thin graded layer occupying a similar stratigraphic position in PL07-43PC.

The abrupt transition from oxic to anoxic conditions in the Cariaco Basin was recorded in PL07-39PC somewhere between 12.6 and 12.75 ka, with the uncertainty largely stemming from the pattern of AMS dates just below the interface. This range of dates

is consistent with the estimate of 12.6 ka previously reported by Peterson *et al.* [1991] based on conventional radiocarbon dates in core V12-104 from the western end of the basin. It is considerably older than the frequently cited value of 11 ka that was originally derived from a single radiocarbon date of organic matter in a *Vema* core by Heezen *et al.* [1958]. The basal age of core PL07-39PC is estimated to be about 22,000 ¹⁴C years.

Sedimentation rates in the dated portion of core PL07-43PC range between 20 and 50 cm/kyr. The reappearance of laminae near the base of this core, indicating the end of an earlier phase of anoxic deposition, can be dated at ~26.8 ka based on linear interpolation, while the basal age of the core is placed at just over 28 ka. In this paper, δ¹⁸O data from the longer record of PL07-43PC are combined with data from PL07-39PC to produce composite records of δ¹⁸O for the last 28 kyr.

The stable isotopic composition of *G. bulloides*, *N. dutertrei*, and the white form of *G. ruber* were analyzed over the entire length of PL07-39PC at 5-cm intervals, while the less abundant pink *G. ruber* were analyzed at 10-cm intervals. On the basis of the sedimentation rate range noted above, the 5-cm interval in PL07-39PC yields a temporal sampling resolution of between ~50 and 170 years. All taxa were analyzed at 10-cm intervals in core PL07-43PC, giving a resolution of between 100 and 500 years in the pre-22 ka section of the composite.

To minimize ontogenetic variations in δ¹⁸O [e.g., Berger *et al.*, 1978], foraminifer specimens were picked from narrow size fractions for analysis, i.e., 355-425 μm for *N. dutertrei* and 212-250 μm for *G. bulloides* and the white morphotype of *G. ruber*. These size fractions were primarily chosen based on the size range most common to the individual species in our sediments but are also common to other published studies [e.g., Curry and Matthews, 1981; Steens *et al.*, 1992]. In the 212-250 μm size range, adequate numbers of the pink morphotype of *G. ruber* were usually not found for analysis because this form is generally larger than the white one [Hemleben *et al.*, 1989]. The size fraction for pink *G. ruber* had to be expanded to 300 μm to obtain enough specimens for isotope measurement. In the 400-600 cm laminated interval in core PL07-39PC, the practice of analyzing narrow size fractions of *G. ruber* had to be further relaxed to the 150-425 μm size fraction because of the scarcity of both the white and pink forms. Isotope analyses were

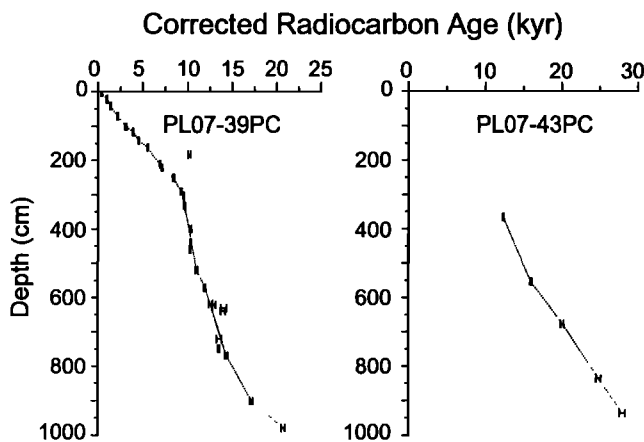


Figure 3. AMS ¹⁴C age models for cores PL07-39PC and PL07-43PC based on analyses of monospecific samples of *G. bulloides* (see Table 1). All dates have been reservoir corrected by 420 years to account for radiocarbon differences between the local surface water and atmosphere. Error bars on the dates (±1σ) are indicated.

made on a Finnigan-MAT 251 mass spectrometer in the Stable Isotope Laboratory of the Rosenstiel School at the University of Miami. All isotopic data are reported as parts per thousand (‰) relative to Pee Dee Belemnite (PDB). Calibration to the PDB standard for CaCO_3 was done through NBS-18 and NBS-19 standards from the National Institute of Standards and Technology. Reproducibility for $\delta^{18}\text{O}$, based on 141 pairs of foraminiferal duplicates, was $\pm 0.08\text{‰}$. All isotope data are available from World Data Center-A for Paleoclimatology at the NOAA National Geophysical Data Center, Boulder, Colorado.

Results

The $\delta^{18}\text{O}$ data from the four taxa analyzed are plotted as time series in Figure 4. Superimposed on each of the records (dotted line) is the change in mean isotopic composition of the whole ocean ($\delta^{18}\text{O}_{\text{water}}$) expected from meltwater addition during deglaciation, as derived from the 17-kyr glacioeustatic sea level record of Fairbanks [1989]. In theory, deviations from this line should represent local

temperature and/or salinity effects [e.g., Fairbanks, 1989]. Over the last 17 kyr, the long-term change in the $\delta^{18}\text{O}$ of *N. dutertrei* generally tracks the $\delta^{18}\text{O}_{\text{water}}$ curve quite well. The average glacial-interglacial amplitude of the $\delta^{18}\text{O}$ signal is about 1.2–1.3‰, with higher-frequency variability of the order of $\sim 0.5\text{‰}$. This observation is consistent with earlier noted suggestions that *N. dutertrei* is a thermocline dweller that calcifies its test over a relatively narrow range of temperatures [Fairbanks *et al.*, 1982; Dunbar, 1983; Curry *et al.*, 1983]. The $\delta^{18}\text{O}$ values for *G. bulloides* follow the $\delta^{18}\text{O}_{\text{water}}$ record fairly closely for the last 6 kyr but tend to be relatively enriched over much of the interval before then. A notable exception occurs at about 14 ka where a pronounced depletion event ($\sim 0.9\text{‰}$) is recorded in the $\delta^{18}\text{O}$ of *G. bulloides*. This sharp deviation correlates stratigraphically with the base of the distinct, fine-grained gray layer that occurs near the top of the oxic sediment interval in these and other cores in the basin. To a lesser extent, this same depletion event is recorded in the $\delta^{18}\text{O}$ of *N. dutertrei* and *G. ruber*.

In contrast to the record of *N. dutertrei*, changes in the long-term $\delta^{18}\text{O}$ of *G. ruber* are considerably larger (~ 2.2 – 2.3‰) than those predicted for the glacial to interglacial isotopic change in seawater alone. Though less densely sampled, $\delta^{18}\text{O}$ values for the pink morphotypes of *G. ruber* are typically lighter than comparable values for the white form.

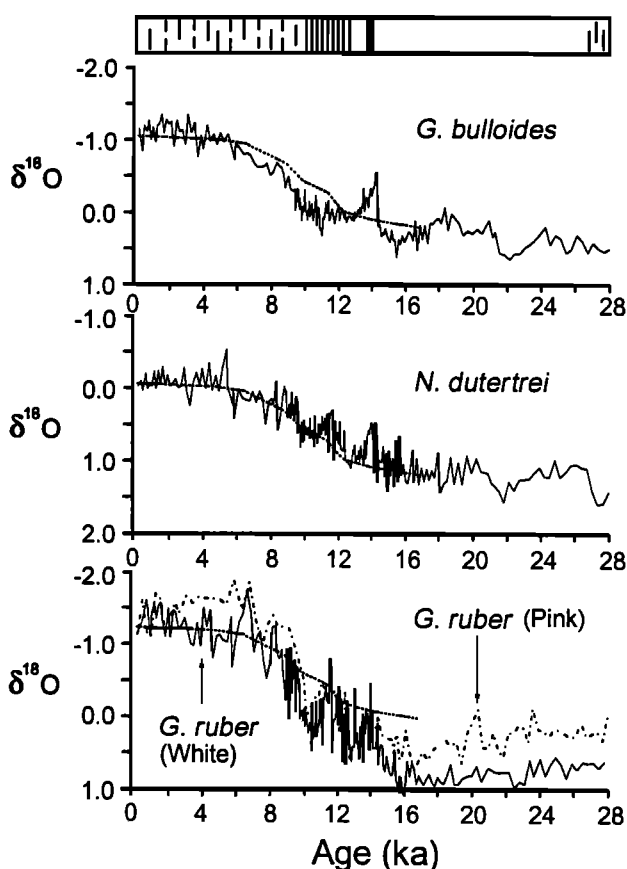


Figure 4. Individual time series of $\delta^{18}\text{O}$ for *G. bulloides*, *N. dutertrei*, and both the white and pink morphotypes of *G. ruber* from the Cariaco Basin. Records shown here represent composite time series produced from patching the longer record of PL07-43PC onto the base of PL07-39PC. Generalized lithologic information is shown across the top (see Figure 2). The dotted line superimposed over each $\delta^{18}\text{O}$ record represents the expected effect of deglaciation and meltwater discharge on the isotopic composition of the whole ocean reservoir [Fairbanks, 1989]. Per mil $\delta^{18}\text{O}$ units are shown relative to the Pee Dee Belemnite standard.

Relationship to Modern Hydrography

Changes in the isotopic composition of seawater through time are not the only factors that affect interpretation of $\delta^{18}\text{O}$ data from foraminifera. Depth habitats, the time of the year at which test calcification occurs, and the potential for disequilibrium fractionation are additional variables that need to be understood in order to maximize the information gained from foraminiferal stable isotope studies. Direct comparison of depth and seasonal data with isotopic compositions of foraminifera collected in vertically stratified plankton tows is probably the most effective way of improving isotope-environment calibrations. Unfortunately, such data do not currently exist for planktonic foraminifera in the Cariaco Basin. Comparison of measured foraminiferal $\delta^{18}\text{O}$ values with values expected for calcite precipitated under equilibrium conditions provides an alternative means of assessing the ecologic niche and paleoenvironmental utility of our taxa.

Measurements of temperature and salinity taken from a Niskin bottle hydrocast during the PLUME-07 Expedition (June 1990) were used to estimate a profile of the $\delta^{18}\text{O}$ of equilibrium calcite for the upper 350 m of the water column (Figure 5). The profile of expected values was constructed using the Craig [1965] revision of the paleotemperature equation of Epstein *et al.* [1953], and the salinity- $\delta^{18}\text{O}_{\text{water}}$ relationship of Craig and Gordon [1965]. Modern (core top) $\delta^{18}\text{O}$ values from the taxa examined in this study (Figure 4) are generally consistent with what is known of their ecology and with the $\delta^{18}\text{O}$ values expected for equilibrium calcite precipitated in the upper water column.

Core top $\delta^{18}\text{O}$ values for *N. dutertrei* (~ 0.0 – 0.1‰) suggest that this species precipitates its test at a depth of ~ 100 m in the Cariaco Basin (Figure 5). This is consistent with numerous other studies which indicate that *N. dutertrei* is a thermocline dweller that provides a good record of deep mixed layer conditions [e.g., Curry and Matthews, 1981; Fairbanks *et al.*, 1980, 1982; Deuser and Ross, 1989]. A near-surface habitat is indicated by the $\delta^{18}\text{O}$ compositions of coretop *G. ruber* (-1.2 to -1.3‰), which closely match equilibrium values calculated from the June SST and salinity data. Although white *G. ruber* have been reported to be out of

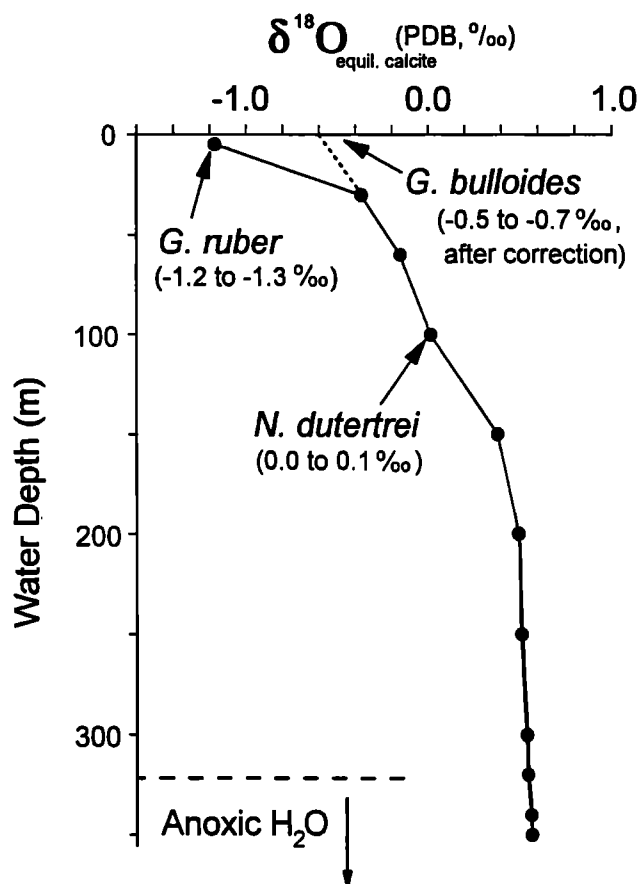


Figure 5. Estimated profile of the $\delta^{18}\text{O}$ of equilibrium calcite for the upper 350 m of the Cariaco Basin water column. Equilibrium values (solid line) were calculated using methods described in the text and measurements of in situ temperature and salinity for Niskin bottle samples (dots) collected during the PLUME-07 coring cruise (June 1990). The dashed line near the top of the profile shows the near-surface change for equilibrium calcite expected for sea surface temperatures of $\sim 22^\circ\text{--}23^\circ\text{C}$ normally found during the winter-spring upwelling season. Late Holocene $\delta^{18}\text{O}$ values for *G. ruber* (-1.2 to -1.3‰ ; see Figure 4) are consistent with near-surface precipitation during nonupwelling conditions, while *N. dutertrei* values (~ 0.0 – 0.1‰) suggest that this species lives in the thermocline at ~ 100 m depth. After correction by $+0.5\text{‰}$ (see text for discussion), *G. bulloides* data (-0.5 to -0.7‰) are consistent with equilibrium calcite values expected for the cooler waters present during the upwelling season.

equilibrium with ambient seawater by an average of about 0.2‰ [Fairbanks et al., 1980, 1982; Williams et al., 1979, 1981; Deuser et al., 1981], Deuser [1987] proposed that the average $\delta^{18}\text{O}$ of *G. ruber* tests settling to the sea floor over the course of one or more years gives a close approximation to the $\delta^{18}\text{O}$ of calcite in equilibrium with surface water of mean annual temperature and salinity. Our observation that pink *G. ruber* are typically more depleted than white *G. ruber* in the same samples is consistent with the suggestion [e.g., Williams et al., 1981; Bé, 1982; Deuser and Ross, 1989] that pink *G. ruber* are restricted to living only in the summer months, while the white forms are more or less found throughout the year.

The core top $\delta^{18}\text{O}$ values of *G. bulloides* are more problematic than the other taxa with respect to the equilibrium profile (solid

line) in Figure 5. Values very close to those recorded by *G. ruber* (-1.0 to -1.2‰) appear inconsistent with what is known about *G. bulloides* association with upwelling here and elsewhere in the tropics. However, evidence from a number of studies strongly suggests that the non-symbiont bearing *G. bulloides* precipitates its test significantly out of equilibrium. On the basis of a suite of sediment trap samples from the Sargasso Sea, Deuser and Ross [1989] proposed a $\delta^{18}\text{O}$ depletion of 0.54‰ for *G. bulloides* relative to predicted equilibrium values. A similar offset from equilibrium of up to 0.5‰ was observed in core top *G. bulloides* by Curry and Matthews [1981]. More recently, laboratory culturing studies of this species by Spero and Lea [1995] have shown a clear deviation from equilibrium that appears to covary with test size as a result of a kinetic fractionation during calcification. Spero and Lea [1995] report that effects of this fractionation can be minimized by isotopically analyzing only specimens larger than $\sim 370\ \mu\text{m}$ in size. In Cariaco Basin sediments, *G. bulloides* are generally much smaller than this, making this approach impossible.

As noted before, SSTs and salinities used in the calculation of the equilibrium calcite profile in Figure 5 were measured in June and should represent values for early in the nonupwelling season. The dashed line in Figure 5 shows the change in the shape of the equilibrium $\delta^{18}\text{O}$ profile expected for the SSTs of $\sim 22^\circ\text{--}23^\circ\text{C}$ that normally occur during the upwelling season [Herrera and Febres-Ortega, 1975; Kinder et al., 1985]. To bring $\delta^{18}\text{O}$ data from *G. bulloides* more in line with these expected equilibrium values, we assume an offset from equilibrium similar to that recommended by Deuser and Ross [1989] and add $+0.5\text{‰}$ to all our *G. bulloides* data. Adding $+0.5\text{‰}$ uniformly to the $\delta^{18}\text{O}$ values of *G. bulloides* brings the core top values into close agreement with predicted values for modern upwelling season conditions and also resolves inconsistencies between *G. bulloides* data and those of other taxa in the glacial (oxic) section. Subsequent figures and discussion utilize these corrected *G. bulloides* values.

Discussion

The $\delta^{18}\text{O}$ data from Cariaco Basin planktonic foraminifera generally show the overall trend toward depleted values expected to accompany the transition from last glacial maximum (LGM) conditions to the present. Differences between the records of individual taxa, however, contain important information on changing local conditions during the past 28 kyr.

Figure 6 shows the combined $\delta^{18}\text{O}$ time series for *G. bulloides*, *G. ruber* (both white and pink), and *N. dutertrei*, with the *G. bulloides* values now uniformly corrected by $+0.5\text{‰}$. To further simplify Figure 6, the individual $\delta^{18}\text{O}$ time series have each been smoothed by first interpolating the data to a constant Δt of 50 years and then applying a five-point moving average. Fifty years was selected as the time step for interpolation since this approximates the highest temporal resolution achieved with the variable combination of sedimentation rates and sampling intervals in these two cores. This procedure effectively overcomes biases that would be introduced with simple smoothing of the raw $\delta^{18}\text{O}$ values and allows us to focus on the major events and trends in the data.

Glacial Conditions in the Cariaco Basin

During the LGM (~ 18 ka), the glacioeustatic drawdown of sea level relative to present is estimated to have been of the order of 120 m [Fairbanks, 1989]. Under these conditions, the physical boundary conditions of the Cariaco Basin would have been substantially different from today. Shallow banks (<100 m) which surround the

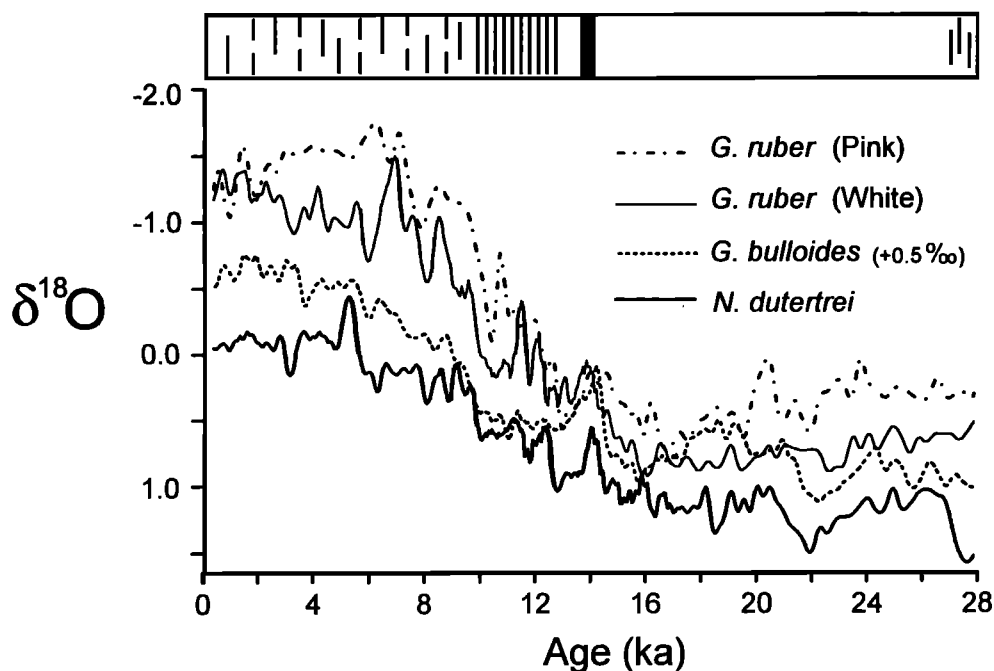


Figure 6. Combined $\delta^{18}\text{O}$ time series for *G. bulloides*, white and pink *G. ruber*, and *N. dutertrei*, with *G. bulloides* values adjusted by a constant $+0.5\text{‰}$ (see text for discussion). Data have been smoothed with a five-point moving average after linear interpolation of the time series to a constant Δt of 50 years.

basin to the north and east would have been largely exposed, and the principal connection with the open Caribbean would have been near its western end at Farallon Centinela (Figure 1). The present sill depth here is ~ 146 m, meaning that glacial sill depths for the Cariaco Basin would have only been of the order of 20–30 m deep.

The effect of sea level on the Cariaco Basin has already been postulated as playing an important role in the composition of planktonic foraminiferal faunas during the last glacial [Peterson *et al.*, 1991]. Prior to 12.6 ka, the foraminiferal assemblages preserved in the sediments were dominated by *G. ruber*, the taxon today characteristic of faunas during the nonupwelling part of the seasonal cycle. Peterson *et al.* [1991] interpreted the high glacial abundance of *G. ruber* and low abundance of *G. bulloides* as evidence for greatly reduced surface productivity and suggested that the major upwelling zone along the coast was shifted seaward of the then largely exposed Tortuga Bank. At 12.6 ka, an abrupt increase in the abundance of *G. bulloides* (to 70–80% of the fauna) was found to be coincident with the first major rise in sea level that accompanied peak meltwater discharge from the Laurentide Ice Sheet into the ocean (meltwater pulse I-A of Fairbanks [1989]). Strong upwelling and increased surface productivity over the Cariaco Basin were interpreted to have begun as rising sea level established more open marine conditions, with the most recent phase of anoxia quickly developing below sill depth in response to the increased rain of organic matter into the deeper waters.

Ignoring for the moment the sharp $\delta^{18}\text{O}$ depletion event at ~ 14 ka, perhaps the most obvious feature of the glacial $\delta^{18}\text{O}$ data in Figure 6 is the overall reduction in between-species differences ($\Delta\delta^{18}\text{O}$) relative to between-species differences in the Holocene. This general convergence of $\delta^{18}\text{O}$ data in the glacial is primarily a result of the larger amplitude of the glacial-interglacial signal in surface-dwelling *G. ruber* as compared to the deeper dwelling *N. dutertrei* (Figure 7). As already noted, both white and pink *G. ruber*

record changes in $\delta^{18}\text{O}$ that are considerably larger (~ 2.2 – 2.3‰) than those predicted for the glacial to interglacial isotopic change in seawater alone, while the long-term variation in *N. dutertrei* follows the reconstructed $\delta^{18}\text{O}_{\text{water}}$ curve relatively well. If the overall departure from the $\delta^{18}\text{O}_{\text{water}}$ curve by *G. ruber* is solely ascribed to temperature change, then it represents about a 4°C cooling of glacial surface waters over the Cariaco Basin. This number is larger than the CLIMAP Project Members [1981] estimate of less than 2°C change for the region during the LGM, but given Cariaco Basin's position along a coast affected by upwelling, the significance of 4°C cooling at this location to the current controversy over tropical SST estimates [e.g., Guilderson *et al.*, 1994] is open to debate.

Although *G. ruber* shows the largest departure from the predicted $\delta^{18}\text{O}_{\text{water}}$ curve during the glacial, the $\delta^{18}\text{O}$ values of *G. bulloides* are also enriched by some 0.3 – 0.5‰ in the interval between 18 and ~ 14 ka (Figure 4). Given this particular species' dominance in the winter-spring upwelling season, it seems logical to suspect that enhanced upwelling and sea surface cooling are responsible. However, the fact that the upwelling season is also the regional dry season suggests that changes in surface salinity need to be considered as well. Numerous studies have suggested that a more arid climate prevailed over northern South America [e.g., van der Hammen, 1974; Schubert, 1988; Markgraf, 1989; Clapperton, 1993] and over tropical Africa [Street and Grove, 1979] during the last glacial. An overall increase in net evaporation (plus lowered sea level) has been linked to significantly higher glacial salinities in marginal seas like the Mediterranean and Red Seas [Thunell *et al.*, 1987, 1988; Thunell and Williams, 1989]. From Venezuela, paleolimnological data from Lake Valencia support the existence of arid lowland climates at the close of the Pleistocene [e.g., Bradbury *et al.*, 1981]. In the Cariaco Basin, arid local conditions, coupled with lowered sea level and more restricted exchange of waters with the open Caribbean, could have resulted in higher salinities that are

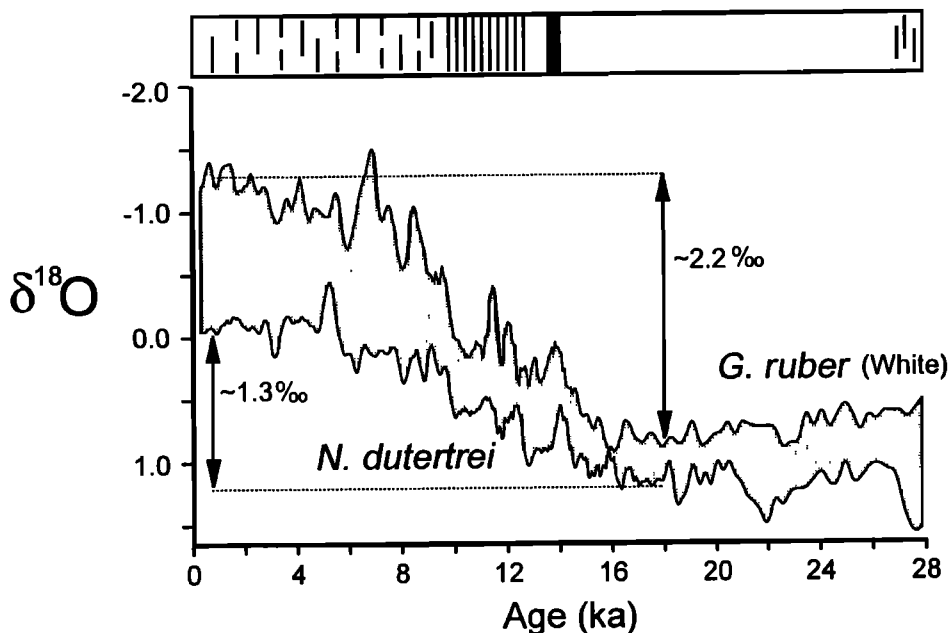


Figure 7. Smoothed $\delta^{18}\text{O}$ time series for white *G. ruber* and *N. dutertrei* illustrating the differences in the glacial-interglacial amplitudes of their respective signals. The larger amplitude of the *G. ruber* signal relative to that of the deeper-dwelling *N. dutertrei* suggests a glacial cooling of Cariaco Basin surface waters of up to $\sim 4^{\circ}\text{C}$.

at least partially recorded in the $\delta^{18}\text{O}$ records of *G. ruber* and *G. bulloides*. High salinities might also help explain the observed dominance of *G. ruber* in glacial sediments of the Cariaco Basin since this species, in addition to its general association with warm, low-productivity conditions, is also one of the most salinity tolerant foraminiferans known. *Locke and Thunell* [1988], for example, found *G. ruber* to dominate in glacial sediments of the Red Sea where high-salinity surface conditions were known to exist. In the Cariaco Basin, higher glacial salinities could presumably have driven local downwelling that helped maintain the deep basin in an oxic state. Though perhaps an appealing scenario, higher salinities and downward mixing would be expected to result in $\delta^{18}\text{O}$ changes that were more uniformly distributed in the water column and more evenly recorded by shallow and deep dwelling taxa. This does not appear to be the case in Cariaco Basin where the glacial-interglacial $\delta^{18}\text{O}$ change in the deeper dwelling *N. dutertrei* allows little room for a large local salinity signal to be superimposed on the global $\delta^{18}\text{O}_{\text{water}}$ signal which already dominates the record (Figure 4). Thus it seems more likely that cooling of the surface waters inhabited by *G. ruber* and *G. bulloides* during the glacial, relative to the depths where *N. dutertrei* lived, is a better explanation of the combined $\delta^{18}\text{O}$ data.

Another important factor that needs to be considered when discussing the temperature implications of the $\delta^{18}\text{O}$ data is simply the role of sill depth in controlling the hydrography of the water column in the Cariaco Basin. During the LGM, the shallow sill depths imposed by lowered sea level should have had a predictable effect on the temperature of the upper water column. A comparison of a modern temperature profile from the Cariaco Basin with one from the adjacent Caribbean (Figure 8) shows the effect of the present 146-m sill depth on the temperature structure in the Cariaco Basin. Above sill depth, the vertical temperature profiles inside and outside the basin are nearly identical. Below sill depth, Cariaco Basin waters are approximately isothermal at $\sim 18^{\circ}\text{C}$, with the

temperature dictated by the temperature of the outside Caribbean waters at 146 m. During the last glacial lowstand of sea level, when sill depth would have been of the order of 25 m or so, temperatures in the Cariaco Basin below that level should have similarly reflected the temperature outside the basin at sill depth. If one assumes no glacial change in SST and a subsurface temperature profile no different from present, then Cariaco Basin deep waters should, in fact, have warmed by several degrees Celsius through the simple shallowing of sill depth. Temperature and $\Delta\delta^{18}\text{O}$ gradients between surface and deep waters would have been reduced as a result, but the reduction in gradients would have been driven by the warming of waters below sill depth and not by surface cooling. This is opposite the pattern of change observed in the Cariaco Basin $\delta^{18}\text{O}_{\text{water}}$ curve records (Figure 7). Furthermore, glacial cooling of surface waters at and above sill depth must have occurred in order to keep *N. dutertrei* from showing a temperature signal superimposed on the $\delta^{18}\text{O}_{\text{water}}$ signal that already accounts for most of the isotopic variability in this taxon.

Though a decrease in glacial SST of up to 4°C appears to be called for by the $\delta^{18}\text{O}$ data, the question remains whether this cooling was due to increased local upwelling of colder subsurface water, or was instead the result of a more uniform cooling of the larger Caribbean region. Stronger upwelling during the glacial might well have been expected along the southern margin of the Caribbean given evidence for stronger, and probably more zonal, glacial trade winds resulting from steepened latitudinal temperature gradients [e.g., *Mix et al.*, 1986]. However, if upwelling was stronger over the Cariaco Basin at that time, the foraminiferal faunas clearly fail to record it in terms of their assemblage makeup [*Peterson et al.*, 1991].

One way to try and discriminate between the effects of upwelling and regional cooling is to again focus on examining the vertical structure of the water column but using taxa more closely associated with the upwelling season. Of the various possible combinations of

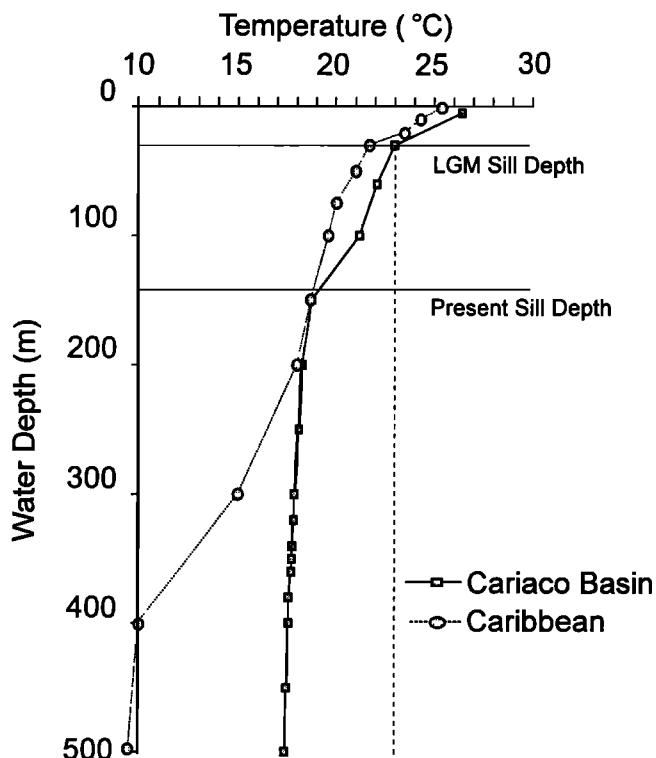


Figure 8. Modern temperature profiles from inside ($10^{\circ}33.26'N$, $64^{\circ}47.05'W$ (this study) and outside ($11^{\circ}20'N$, $64^{\circ}30'W$ [Okuda et al., 1969]) the Cariaco Basin showing the effect of present (146 m) and inferred glacial sill depths (last glacial maximum; ~25 m) on temperatures within the basin. The vertical dashed line indicates the temperature profile to be expected below sill depth during the last glacial if temperatures in the upper water column at that time were no different than present. The $\delta^{18}O$ data from the Cariaco Basin do not support the warming implied by this model.

$\delta^{18}O$ records in Figure 6, the records of *G. bulloides* and *N. dutertrei* most closely parallel each over the last 28 kyr (Figure 9). This observation would seem to suggest that *N. dutertrei*, in general, record deeper conditions during the upwelling season. Interestingly, the $\delta^{18}O$ gradient between *G. bulloides* and *N. dutertrei* (Figure 9) during the last glacial does not appear to have differed appreciably from that observed in the late Holocene, suggesting that thermal gradients in the water column related to upwelling were approximately the same over the two time intervals. This has two important implications, namely, that (1) upwelling was physically active in the Cariaco Basin during the last glacial, despite faunal evidence to the contrary [Peterson et al., 1991]; and (2) glacial upwelling intensity, on average, differed little from Holocene levels. The latter inference suggests that cooling of surface waters over the Cariaco Basin during the LGM may have been part of a larger regional trend affecting the Caribbean Sea.

The apparent discrepancy between foraminiferal evidence for low glacial productivity [Peterson et al., 1991] and isotopic evidence for active upwelling can probably be explained by considering the effect of a 25-m sill depth on nutrient distributions in the glacial Cariaco Basin. Waters spilling over the sill and filling the basin at that time from the open Caribbean Sea would have come from the most nutrient-depleted waters that normally charac-

terize the near surface. Thus, even if upwelling was physically active, as the $\Delta\delta^{18}O$ data suggest (Figure 9), the upwelled waters are likely to have been quite nutrient depleted to begin with, a factor reflected in the low-productivity foraminiferal assemblage found at that time. Lower surface production and the decreased oxygen demand created by sinking organic detritus would have directly contributed to the oxic conditions recorded in glacial-age sediments from the Cariaco Basin.

Pleistocene-Holocene Transition

Between 12.6 and about 10 ka, evidence for much higher surface productivity comes from the increased abundance of *G. bulloides* and from the thickness and character of the biogenic-rich sediment laminae [Peterson et al., 1991; Hughen et al., 1996a, b]. Our $\delta^{18}O$ data support stronger upwelling as the cause of this high productivity. During this interval, the $\delta^{18}O$ differences between *G. bulloides* and *N. dutertrei* (Figure 9) decrease such that both the shallow and deeper dweller are recording virtually the same isotopic signal, a pattern consistent with the stronger vertical advection and better mixing of the upper water column expected of more vigorous upwelling. A similar convergence of $\delta^{18}O$ data between *G. bulloides* and *N. dutertrei* during upwelling events has been reported in plankton tow studies from the Arabian Sea [Steens et al., 1992] and in sediment trap work carried out in the San Pedro Basin off California [Thunell and Sautter, 1992].

G. bulloides $\delta^{18}O$ values diverge again from those of *N. dutertrei* after about 10 ka, at a level in the sediments where the abundance of *G. bulloides* drops sharply and where the character of the laminae changes from distinctly laminated below to more faintly laminated above. All of these lines of evidence point to a reduction in surface productivity and upwelling and a transition to conditions that have generally persisted for most of the last 10 kyr.

A Late Glacial Freshwater Event?

Within the preanoxic sediment section, the other major feature of interest is the pronounced negative excursion that occurred near 14 ka. Though this sharp depletion event is recorded most clearly in the $\delta^{18}O$ data of *G. bulloides* (~0.9‰), it shows up to some extent in the records of all taxa. As previously noted, the event coincides stratigraphically with deposition of the distinctive gray layer found in cores from throughout Cariaco Basin. The fine-grained, foraminifer-poor and clay-rich nature of this layer suggests a terrigenous source and the very depleted $\delta^{18}O$ values are consistent with a strong freshwater influence. Two major possibilities exist to explain this event. The first is that this $\delta^{18}O$ anomaly is related to a period of higher regional rainfall which increased river discharge into the southern Caribbean. Although river runoff into the Cariaco Basin has little influence on surface salinities at present [Ljøen and Herrera, 1965], the local effects of increased rainfall might have been exaggerated near the close of the last glacial when sea level was still low, and the basin was much more isolated from the open Caribbean. However, independent evidence of a 14 ka precipitation (or other type of climatic) event at other sites in northern South America is sparse. One site in Columbia contains evidence of a higher lake level at approximately this time [van der Hammen et al., 1981], but most others do not [van Geel and van der Hammen, 1973; Markgraf, 1989]. In North America, the story is different. Evidence for unusually wet conditions between about 14 and 13 ka comes from work in the southeastern United States [Grimm et al., 1993; Kneller and Peteet, 1993] and from the western Great Basin [Benson, 1991]. Broecker [1994] has referred to this as the "trans-

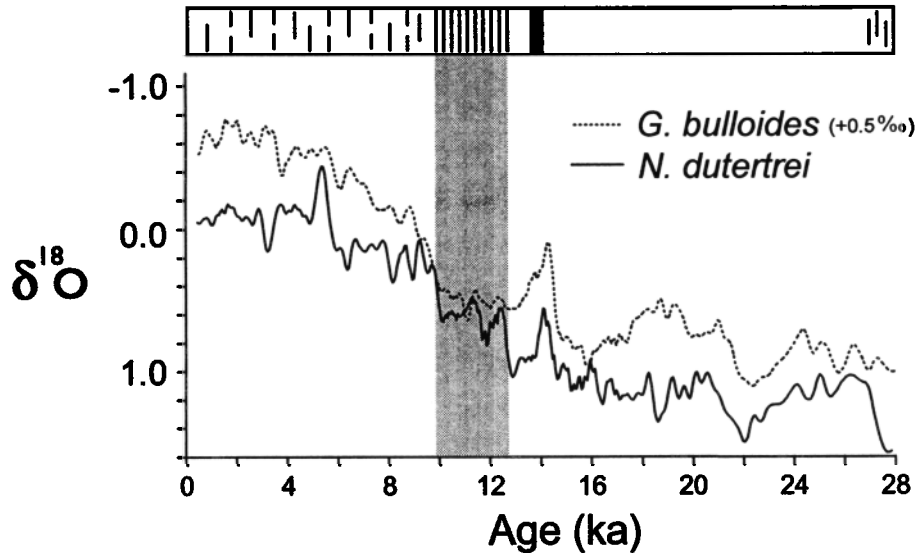


Figure 9. Comparison of smoothed $\delta^{18}\text{O}$ data from the upwelling-sensitive *G. bulloides* and the deeper-dwelling *N. dutertrei* (Figure 6). The general convergence of values in these two records between 12.6 and ~ 10 ka suggests a period of stronger upwelling and more vigorous vertical mixing in the Cariaco Basin during deglaciation. Stronger upwelling in this time interval is consistent with foraminiferal and lithologic evidence for high surface productivity.

U.S. wet event” and suggested that it is somehow related to changes in the mode of deep water formation in the North Atlantic. The similar timing of the $\delta^{18}\text{O}$ anomaly in the Cariaco Basin suggests that wet conditions of this interval may have extended farther south than previously believed.

Another possible explanation for the 14 ka low salinity event is that it represents meltwater dilution caused by the deglaciation of the northern Andes. The chronology of this event is difficult to infer from available glacial geological data, but most studies suggest that the initial deglaciation of the Andes could have begun around 14 ka [Schubert and Clapperton, 1990; Rodbell, 1993; Clapperton, 1993]. Weingarten [1991], in a lake-based study, suggests that abrupt warming, and hence melting, occurred in the Venezuelan Andes at 13.8 ka, a time very close to that of the Cariaco Basin $\delta^{18}\text{O}$ event. However, regional topography dictates that most meltwater generated from the glaciers of the northern Andes would have discharged to the east through the Amazon and Orinoco Rivers, rather than to the north and directly into the southern Caribbean. During the late glacial and in the early phase of deglaciation, low sea level would have further inhibited direct meltwater transport from these rivers into the Caribbean because of shallow sills and topography in the vicinity of Trinidad. In piston cores from the Amazon Fan, Showers and Bevis [1988] reported a tropical freshwater “spike” in $\delta^{18}\text{O}$ records that initiated about 13.5 ka, peaked at 9.6 ka, and terminated about 6 ka. In an earlier study, Showers and Margolis [1985] noted anomalously depleted $\delta^{18}\text{O}$ values in fine-fraction (coccolith) carbonate from the southern Venezuelan Basin but beginning only later at about 11.5 ka. This discrepancy in timing was cited by Showers and Bevis [1988] as evidence of the effects of sea level and topography in controlling freshwater input to the Caribbean from the major rivers that drain the South American continent upstream. Given the regional topographic constraints, we believe it more likely at present that the Cariaco Basin $\delta^{18}\text{O}$ record at ~ 14 ka is recording a local pluvial signal than a direct signal of Andes meltwater influence, though we

note that increased precipitation and increased melting of Andean glaciers in the region may be inherently linked.

Holocene Conditions

Between ~ 7 and 6 ka, $\delta^{18}\text{O}$ values of both the white and pink forms of *G. ruber* are their most depleted of the last 28 kyr (Figure 6). During this same interval, $\delta^{18}\text{O}$ data from *G. bulloides* and *N. dutertrei* are intermediate between early and late Holocene values. This period of minimum *G. ruber* $\delta^{18}\text{O}$, centered on about the mid-Holocene, corresponds in time to a warm moist interval when temperatures and lake levels were higher than today throughout much of the northern American tropics [Bradbury et al., 1981; Deevey et al., 1983; Leyden, 1984, 1985; Piperno et al., 1990] and Africa [Street and Grove, 1979; Street-Perrott and Harrison, 1985; Kutzbach and Street-Perrott, 1985]. Crowley and North [1991], summarizing evidence for warmer mid-Holocene climates, noted that much of the apparent temperature increase of this period may represent seasonal (summer) warmth rather than year-round warmth. The $\delta^{18}\text{O}$ data of pink *G. ruber*, in particular, with its broad minimum in the mid-Holocene, would seem to support a change in summer conditions that enhances the overall seasonal contrast ($\Delta\delta^{18}\text{O}$ of *G. bulloides*-pink *G. ruber*) in the Cariaco Basin. Thus warming of summer SSTs in the region is one possible way to explain the observed pink *G. ruber* data. Alternatively, depleted $\delta^{18}\text{O}$ values recorded by pink *G. ruber*, and to a lesser extent by the white form, could be the result of lower regional surface salinities. On the basis of similar depleted values observed in an ostracod $\delta^{18}\text{O}$ record from Lake Miragoane, Haiti, Hodell et al. [1991] suggested that increased precipitation relative to evaporation characterized the mid-Holocene of the Caribbean. Changes in precipitation patterns were linked by Hodell et al. to the changing intensity of the annual cycle at this latitude. Unfortunately, further discrimination between local temperature and/or salinity-precipitation mechanisms for this time interval is not yet possible with existing data. Ongoing studies

of pollen, clay mineralogy, and other paleoclimate proxies that are part of the larger Cariaco Basin effort may eventually shed light on this and other questions.

Conclusions

Oxygen isotopic records from multiple species of planktonic foraminifera have been generated in well-dated sediment cores from the Cariaco Basin, off the northern coast of Venezuela. These records provide a high-resolution, subcentury-scale view of paleoenvironmental change in the southern Caribbean over the 28 kyr and lead to the following conclusions.

The $\delta^{18}\text{O}$ data from late Holocene specimens of *G. bulloides*, *G. ruber* (both pink and white morphotypes), and *N. dutertrei* are generally consistent with what is expected based on knowledge of these species' ecologies and of the local hydrographic setting. After correction by +0.5‰ for nonequilibrium precipitation, *G. bulloides* $\delta^{18}\text{O}$ data can be used to monitor surface conditions during the winter-spring upwelling season. The $\delta^{18}\text{O}$ values from pink *G. ruber* are generally the most depleted of all taxa and provide information on surface conditions during the warmest and/or wettest summer months. White *G. ruber* data provide perhaps the best record of "average" near-surface conditions, while $\delta^{18}\text{O}$ data from *N. dutertrei* support its interpretation as a deep dweller (~100 m) that lives near the base of the local thermocline.

During the last glacial, $\delta^{18}\text{O}$ data from shallow-dwelling *G. ruber* and generally reduced interspecific differences are consistent with a cooling of surface waters over the Cariaco Basin of the order of 3°–4°C. The gradients in $\delta^{18}\text{O}$ between the upwelling sensitive *G. bulloides* and deeper dwelling *N. dutertrei* at this time are comparable to gradients observed in the late Holocene, indicating that upwelling conditions were not significantly different between the two time intervals. These observations suggest that the 3°–4°C glacial decrease in SST recorded by *G. ruber* in the Cariaco Basin may be part of a regional cooling trend in the ice age Caribbean and not the result of local changes in upwelling.

In the interval between 12.6 and ~10 ka, the convergence of $\delta^{18}\text{O}$ values from *G. bulloides* and *N. dutertrei* indicates more vigorous upwelling and vertical mixing in the Cariaco Basin, presumably driven by stronger trade winds. This scenario is strongly supported by other lithologic and faunal evidence from the sediments.

A pronounced $\delta^{18}\text{O}$ depletion event recorded in all four foraminiferal taxa about 14 ka coincides with deposition of a fine-grained, gray colored layer that is present in cores throughout the Cariaco Basin. This depletion event appears to mark a short period of increased freshwater influence whose effects may have been amplified in a basin still partially isolated by lowered glacial sea level.

In the mid-Holocene (~6–7 ka), a broad interval of depleted $\delta^{18}\text{O}$ values in pink *G. ruber* seems to record warmer summer SSTs and/or increased regional precipitation and run off. Conditions during this period may be the result of an enhanced annual cycle that affects temperature and rainfall in the Caribbean region.

Acknowledgments. This work constitutes a portion of the senior author's Ph.D. dissertation at the Rosenstiel School, University of Miami, Florida. Financial support for this work has come from U.S. National Science Foundation Grants OCE-9116028 and OCE-9403459 to L.C.P. and from Taiwan National Science Council Grants NSC84-2611-M110-008OS and NSC85-2611-M110-005OS to H.-L.L. We thank P.K. Swart for use of the Stable Isotope Laboratory, RSMAS, during the course of this study. Constructive and thorough reviews by R. Thunell, B. Linsley, and A. McIntyre are greatly appreciated. PLUME-07 cores are archived at the

Lamont-Doherty Earth Observatory Deep-Sea Sample Repository, Columbia University, where curation is supported by the National Science Foundation.

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(Received January 6, 1996; revised December 5, 1996; accepted January 16, 1997.)