

## Seasonality and stable isotopes in planktonic foraminifera off Cape Cod, Massachusetts

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[1] Monthly samples of stratified plankton tows taken from the slope waters off Cape Cod nearly 25 years ago are used to describe the seasonal succession of planktonic foraminifera and their oxygen isotope ratios. The 15°C seasonal cycle of sea surface temperature (SST) accounts for a diverse mixture of tropical to subpolar species. Summer samples include various *Globigerinoides* and *Neogloboquadrina dutertrei*, whereas winter and early spring species include *Globigerina bulloides* and *Neogloboquadrina pachyderma* (dextral). *Globorotalia inflata* lives all year but at varying water depths. Compared with the fauna in 1960–1961 (described by R. Cifelli), our samples seem warmer. Because sea surface salinity varies little during the year,  $\delta^{18}\text{O}$  is mostly a function of SST. Throughout the year, there are always species present with  $\delta^{18}\text{O}$  close to the calculated isotopic equilibrium of carbonate with surface seawater. This raises the possibility that seasonality can be estimated directly from the range of  $\delta^{18}\text{O}$  in a sediment sample provided that the  $\delta^{18}\text{O}$ -salinity relationship is the same as today.

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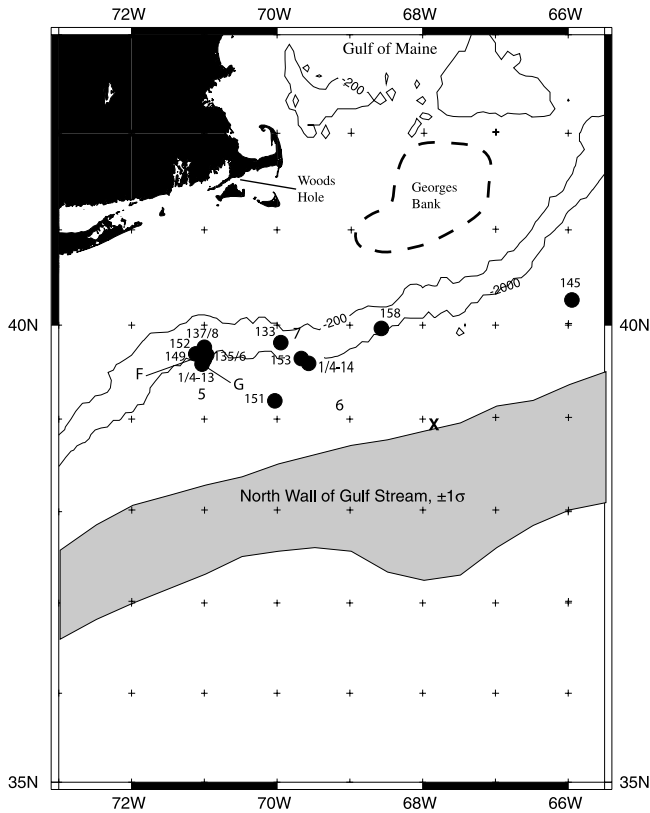
### 1. Introduction

[2] The usefulness of planktonic foraminifera as proxies for past oceanographic conditions depends entirely on how well they are calibrated to their biological, chemical, and physical surroundings. Studies of plankton tow material [Be, 1960; Fairbanks *et al.*, 1980; Kahn and Williams, 1981; Williams and Be, 1981; Kohfeld *et al.*, 1996] and sediment trap collections [Erez and Honjo, 1981; Curry *et al.*, 1983; Hemleben *et al.*, 1985; Deuser and Ross, 1989; Sautter and Thunell, 1989, 1991] have established the geographic and depth range of species, and culturing experiments have shown how the planktonic foram test reflects the chemical and physical environment [Erez and Luz, 1982; Spero *et al.*, 1997; Bemis *et al.*, 1998]. As paleoceanographic studies increase in sophistication, we have a greater need to understand how the planktonic foraminiferal fauna reflect the environment in different locations. The ideal situation would be to have long time series of seasonal faunal data wherever important interpretations are made from sediment core data. This is not likely to happen anytime soon, but as we show in this paper, it is possible to mine marine biological collections to help calibrate paleoproxies.

[3] Recently, we have been sediment coring in the waters off Cape Cod to complement earlier paleoceanography studies to the north off Nova Scotia [Keigwin and Jones, 1995; Keigwin *et al.*, 2005]. The slope water region immediately south of Cape Cod and the islands has been studied intensively in other disciplines because of its

proximity to Woods Hole (Figure 1). In general, the slope water system is driven by the interaction between the buoyancy-driven flux of cold fresh water out of the Labrador Sea and around the Grand Banks and the wind-driven transport of warm and salty water in the Gulf Stream as it departs Cape Hatteras. The large-scale system is reviewed by Csanady and Hamilton [1988] and Loder *et al.* [1998] and is too complex to describe in detail here. Because the plankton samples described here came from north of 39°N, just off the continental shelf, we are concerned here with processes that involve the shelf break front and its associated current and the Gulf Stream. The front separates the fresh waters over the shelf from the saltier waters offshore, and the density contrast between them supports the equatorward slope break current. Ekman transport is responsible for seaward export of shelf water, and shoreward advection of Gulf Stream water occurs along isopycnals at greater depth [Csanady and Hamilton, 1988]. These transports are small and insufficient to mobilize coarse-grained sediment such as planktonic foraminifera, but they must affect their spatial distribution in surface waters.

[4] The planktonic foraminifera of the “slope waters” off Cape Cod have been examined previously by Cifelli [1962, 1965] and Fairbanks *et al.* [1980]. Here we discuss the planktonic foraminifera and their oxygen isotope composition from a time series of 15 monthly plankton tows from the slope waters off Cape Cod taken by P. Wiebe and colleagues in 1981 and 1982 [Miller *et al.*, 1991] (Figure 1). These samples were collected using the stratified tows of the multiple opening and closing net and environmental sampling system (MOCNESS). We document the seasonal succession of planktonic foraminifera and infer



**Figure 1.** MOCNESS and other plankton tow locations discussed in the text in relation to bathymetry (200 and 2000 m contours), the Gulf Stream, Georges Bank, and the Gulf of Maine. Cifelli [1962] stations from August 1960, October 1960, January 1961, and May 1961, identified as F, 5, G, and both 6 and 7, respectively. The Fairbanks *et al.* [1980] MOCNESS position is marked by cross.

their position in the water column from the oxygen isotope ratio of their tests ( $\delta^{18}\text{O}$ ).

## 2. Methods

[5] Samples for this study were collected in a series of monthly nighttime plankton tows in the slope waters from 1981 to 1982 [Miller *et al.*, 1991]. The purpose of that sampling was the study of copepod populations, which is typically done with a MOCNESS configured with 333  $\mu\text{m}$  nets and a 1  $\text{m}^2$  sample area. Tows were generally made at 100 m intervals, beginning at 1000 m below the surface. Occasionally, a smaller MOCNESS (1/4  $\text{m}^2$ ) was deployed, with 63  $\mu\text{m}$  nets. Most MOCNESS deployments occurred after the water column was profiled with bathythermographs (BTs). We focused on samples from the upper 100 or 200 m of the water column.

[6] Samples were archived in glass quart jars with 5% formalin and sodium borate as a buffer. Some of the samples were splits. Over the course of 20 years the buffer was sometimes replenished, but by the time we began this study in November 2002 some samples had low pH and no calcareous plankton, and in some samples, carbonate shells

were present but partially dissolved. On the other hand, some samples had abundant pteropods (aragonite, which is more prone to dissolution) but no foraminifera (Table 1). Where present, foraminifera and pteropods were obvious at the bottom of the jars. Foraminifera were concentrated by passing the samples through a 1 mm sieve to separate the larger plankton. The smaller fraction was allowed to settle, and the contents of the jars were swirled to suspend the larger and less dense particles. These were poured off, and the process was repeated several times. Finally, the remainder was passed through a stack of sieves, and the foraminifera were picked from the wet screens. Foraminifera smaller than 333  $\mu\text{m}$  were found in all of the samples, which must reflect clogging of the nets, and their abundance was greater in the 63  $\mu\text{m}$  (“1/4 MOC”) samples. Because of concerns about preservation, split accuracy, the extent of subsampling, collection efficiency of the nets, thoroughness of our concentration method, and difficulty of picking specimens among copepods and gelatinous plankton, our abundance and species frequency data are not quantitative. Furthermore, where a species was very abundant, not all were picked and counted (Table 1).

[7] Depending on shell size, as few as 4 and as many as 15 specimens of planktonic foraminifera were chosen for stable isotope analysis. Where they were abundant enough, analyses were made on more than one size fraction. Samples were roasted for an hour at 370°C to remove fresh organic components that could evolve  $\text{CO}_2$  during hydrolysis. Stable isotope ratios were measured on a VG Prism mass spectrometer at the National Ocean Sciences Accelerator Mass Spectrometer Facility at Woods Hole Oceanographic Institution (WHOI). Results are presented with respect to Pee Dee belemnite (standard) (PDB) through analysis of the carbonate standards NBS-18 and NBS-19. The  $\delta^{18}\text{O}$  of calcite precipitated in equilibrium with sea surface conditions was calculated using methods described elsewhere [Keigwin, 1996]. Sea surface temperature (SST) was taken from the BT data collected near each plankton tow, and sea surface salinity came from the climatology of a 1° box centered on 39°30'N and 70°00'W (R. Curry, WHOI, personal communication, 2003).

## 3. Results

[8] Table 1 summarizes the distribution of planktonic foraminifera found in the MOCNESS samples from 1981 to 1982. In general, it appears that sampling during the warmer time of the year (June–October) resulted in the most species. In those warm months the fauna is distinctly weighted by the abundance of *Orbulina universa*, *Globigerinoides sacculifera*, *Globigerinoides ruber* (white and pink), and *Globigerinoides conglobatus*. However, with no small mesh tow data from summer months we cannot exclude the possibility that we have missed smaller, colder fauna. It also seems that the fauna may be dominated by *Globorotalia inflata* year-round, although the two earliest samples (April and May 1981) were barren of foraminifera. The next most abundant and prevalent species is *Neogloboquadrina dutertrei*, which is most common in summer samples but present through the winter into early

**Table 1.** Abundance of Selected Planktonic Foraminifera in MOCNESS Samples, 1981–1982<sup>a</sup>

Date	MOC	SST, °C	Depth, m	Abundance <sup>b</sup>		Volume, m <sup>3</sup>	<i>G. infl.</i>	<i>G. trunc.</i>	<i>P. obliq.</i>	<i>N. duter.</i>	<i>N. p. right.</i>	<i>G. bull.</i>	<i>Orb.</i>	<i>G. sacc.</i>	<i>G. ruber white.</i>	<i>G. ruber pink.</i>	<i>G. cong.</i>	<i>G. aequi.</i>	<i>H. pelag.</i>	<i>G. glut.</i>	<i>G. scit.</i>
				PF	Pt																
29 Apr 1981	133	13	0–100	N	N	366.3															
29 May 1981	135	13.3	0–100	N	N	382.1															
29 June 1981	136	20.6	0–100	A	VR	1437.3	XX		XX				17	4		9	1				
28 July 1981	137	24.0	0–100	A	A	484	X	4	XX				15	26	17	XX	2	x			
19 Aug 1981	138	23.5	0–100	C	F	950.6	XX		20				6	1	2	11					
3 Oct 1981	145	20.54	0–200	A	C	1840.2	XX	6	XX				15	40	10	56	14	6			
27 Oct 1981	148	15.10	0–100	VR	VA	438.6	3				3				1						
27 Oct 1981	1/4-11		0–200	R	C		5			4	1										
23 Nov 1981	149	12.02	0–100	R	F	375.6	X	1		cf											
24 Nov 1981	1/4-12		0–200	VR	N		X				cf										
13 Dec 1981	151	16.45	0–100	C	C	493.1	XX	X	1									1			
			100–200			819.3	XX	X	1			1				1					
			200–300			578.3	X	X	X			3									
11 Dec 1981	1/4-13		0–200	VA	C		XX	XX	X	X											
5 Jan 1982	152	13.3	0–100	R	F	552.9	X	1													
8 Feb 1982	153	9.5	0–100	C	C	530.9	3	33	2		1					1	1				
			100–200				2	5													
9 Feb 1982	1/4-14		0–200	R	C		9	X	1	X	18	8							2		x
15 Mar 1982	158	11.85	0–100	F	F	617.1	X	1			2	2									
14 Mar 1982	1/4-17		0–200	C	C		X		X	XX	X	X								X	
2 May 1982	1D-175	12.5	0–75	C	C	272	3			XX	XX	XX		1							2

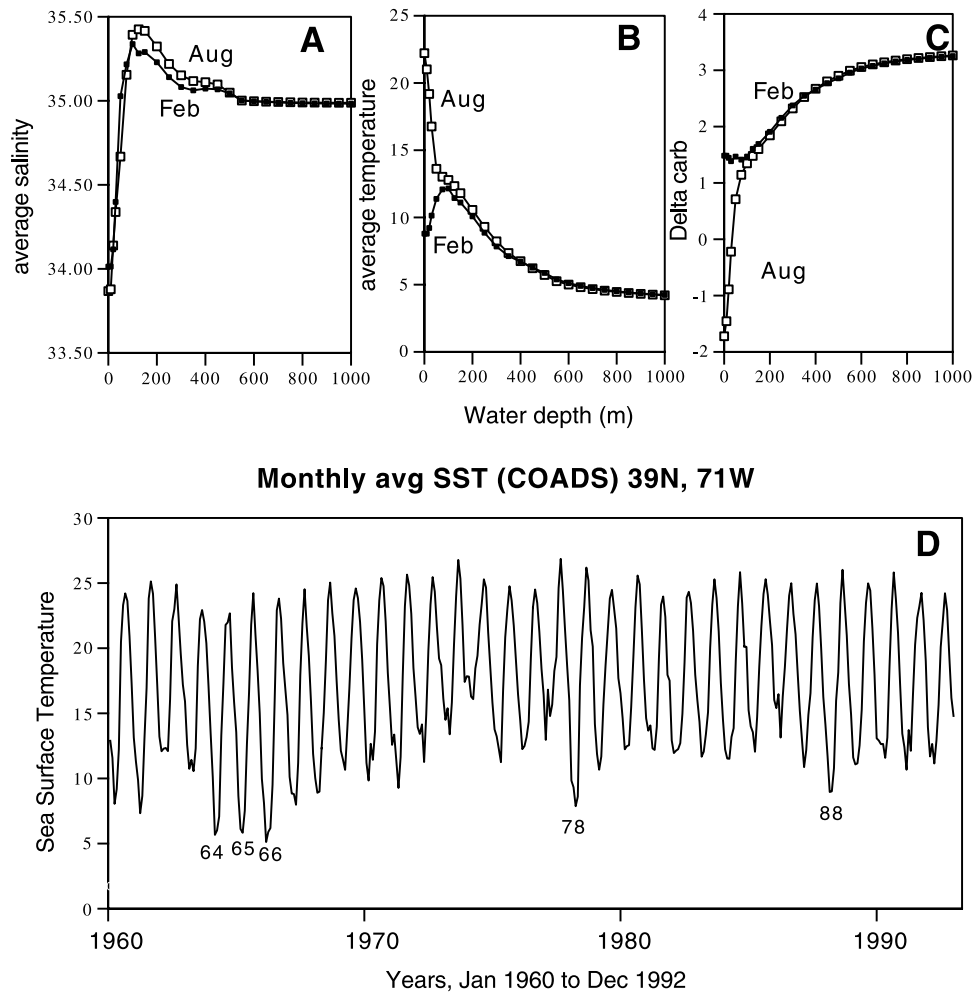
<sup>a</sup>*G. infl.*, *Globorotalia inflata*; *G. trunc.*, *Globorotalia truncatulinoides*; *P. obliq.*, *Pulleniatina obliquiloculata*; *N. duter.*, *Neogloboquadrina deuteri*; *N. p. right.*, *Neogloboquadrina pachyderma right*; *G. bull.*, *Globigerina bulloides*; *Orb.*, *Orbulina*; *G. sacc.*, *Globigerinoides sacculifera*; *G. ruber white.*, *Globigerinoides ruber white*; *G. ruber pink.*, *Globigerinoides ruber pink*; *G. cong.*, *Globigerinoides conglobatus*; *G. aequi*, *Globigerinella aequilateralis*; *H. pelag.*, *Hastigerina pelagica*; *G. glut.*, *Globorotalia glutinata*; *G. scit.*, *Globorotalia scitula*; bold, samples for δ18O (see Table 2); X, number not counted; XX, number not counted but many present.

<sup>b</sup>Abundance of planktonic foraminifera (PF) and pteropods (Pt): VA, very abundant; A, abundant; C, common; F, few; R, rare; N, none.

**Table 2.** Stable Isotope Results on Planktonic Foraminifera From Slope Water MOCNESS Series, for 1981–1982<sup>a</sup>

MOC	Date	Species <sup>b</sup>	Size, $\mu\text{m}$	Number <sup>c</sup>	Notes <sup>d</sup>	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$
136	29 Jun 1981	<i>G. ruber pink</i>	250–400	9		1.19	–1.70
		<i>Orbulina</i>	500	6		2.14	–0.40
		<i>N. dutertrei</i>	350–400	5		2.36	–0.21
137	28 Jul 1981	<i>G. inflata</i>	400	5		0.24	–1.00
		<i>G. inflata</i>	300–350	8		0.92	0.06
		<i>N. dutertrei</i>	300–400	5		2.74	–1.30
		<i>G. ruber white</i>	150–250	12		1.48	–1.91
		<i>G. ruber pink</i>	150–250	12		1.60	–2.15
			300–400	7		1.84	–2.32
			450–550	6		1.83	–2.17
		<i>Orbulina</i>	500	6		3.04	–1.60
		<i>G. sacculifer</i>	150–250	8	1	1.54	–2.07
			250–300	7		1.98	–2.08
138	20 Aug 1981	<i>G. inflata</i>	400–500	6		2.28	–1.92
		<i>G. inflata</i>	300–350	10		0.50	0.37
		<i>N. dutertrei</i>	300–400	6	2	2.17	–0.22
		<i>G. ruber pink</i>	300–350	7		1.89	–2.04
		<i>Orbulina</i>	450–550	5		2.18	–0.28
145	3 Oct 1981	<i>G. ruber pink</i>	250–355	10		1.11	–1.49
			350	8		1.22	–1.35
			350–400	7		1.25	–1.27
			400–500	4		1.37	–1.41
		<i>G. ruber white</i>	250–355	6		1.03	–1.49
		<i>G. sacculifer</i>	250–355	10		1.50	–1.24
			355–400	9		1.75	–1.13
			400–500	5	1	1.88	–1.41
		<i>Orbulina</i>	500–700	6		1.82	–0.31
		<i>G. inflata</i>	250–355	8		0.62	0.03
			355–500	7		0.64	–0.44
		<i>N. dutertrei</i>	250–355	8		1.48	–0.49
			355–500	7		1.88	–0.64
		<i>G. truncatulinoides</i>	250–355	5	3	0.45	0.18
		<i>P. obliquiloculata</i>	355–500	8		0.83	–0.59
			500–600	4		0.36	–1.07
		<i>G. conglobatus</i>	355–500	5		1.19	–1.40
151	13 Dec 1981	<i>G. truncatulinoides</i>	500–600	4		1.69	–1.06
			250–355	6	3	0.15	0.12
			355–500	4	4	0.50	0.38
		<i>G. inflata</i>	150–250	8		0.15	0.00
			250–355	9		0.43	0.14
1/4 MOC 13	15 Dec 1981		355–500	8		0.49	0.45
		<i>N. pachyderma</i>	150–250	15	5	0.06	0.17
		<i>G. truncatulinoides</i>	150–250	12	3	–0.48	–0.13
		<i>G. inflata</i>	250–355	7		0.28	0.39
152	6 Jan 1982		355–500	5		0.24	0.36
		<i>G. truncatulinoides</i>	250–355	9	5	0.22	0.36
			355–500	7	5	0.30	0.36
153	6 Feb 1982		500–600	5	5	0.35	0.12
		<i>N. pachyderma</i>	150–250	12	5	0.09	0.78
		<i>G. bulloides</i>	150–250	12		–1.89	0.40
1/4MOC 14 1/4MOC 17	9 Feb 1982 14 Mar 1982		250–355	8		–1.54	0.39
		<i>G. inflata</i>	150–250	12		0.02	0.77
			250–355	8		0.28	0.83
		<i>N. pachyderma</i>	150–250	12	5	0.05	0.80
		<i>G. glutinata</i>	150–250	12		–0.08	0.72
158	15 Mar 1982	<i>G. inflata</i>	250–355	8		0.31	0.82
			355–500	4		0.36	0.72
		<i>G. bulloides</i>	150–250	12		–1.74	0.39
175	2 May 1982		250–355	10		–1.23	0.46
			355–425	6		–1.23	0.27
			425–500	4		–0.94	0.44

<sup>a</sup>Results are in ‰, PDB.<sup>b</sup>*G. ruber pink*, *Globigerinoides ruber pink*; *N. dutertrei*, *Neogloboquadrina deuterei*; *G. inflata*, *Globorotalia inflata*; *G. ruber white*, *Globigerinoides ruber white*; *G. sacculifera*, *Globigerinoides sacculifera*; *G. truncatulinoides*, *Globorotalia truncatulinoides*; *P. obliquiloculata*, *Pulleniatina obliquiloculata*; *G. conglobatus*, *Globigerinoides conglobatus*; *N. pachyderma*, *Neogloboquadrina pachyderma*; *G. bulloides*, *Globigerina bulloides*; *G. glutinata*, *Globigerinita glutinata*.<sup>c</sup>Number of shells analyzed.<sup>d</sup>Notes are 1, without sacc; 2, 4–4.5 chambers, small umbilical teeth; 3, left; 4, three left, one right; 5, right.



**Figure 2.** Climatology near most slope water observations in this study (39°N, 71°W). Depth profiles of (a) salinity and (b) temperature from HydroBase were provided by R. Curry (WHOI). (c) The  $\delta^{18}\text{O}$  of  $\text{CaCO}_3$  is precipitated in equilibrium, as calculated using the data in Figures 3a and 3b and Shackleton [1974]. (d) Monthly average SST from the COADS database is shown for the period from January 1960 to December 1992. Sampling years discussed in this study and several especially cold winters are identified.

spring. *Globigerina bulloides* is present, although sometimes in very low abundance, from October through the spring. *Globorotalia truncatulinoides* and *N. pachyderma* (dextral) were present from October through March, but the former was only abundant beginning in December, whereas the latter was abundant as late as March. Other species are present only occasionally and are too rare or sporadic to establish a seasonal preference. The left-coiling variety of *N. pachyderma* was not seen at all.

[9] Stable isotope results on the more common species are listed in Table 2. The lowest  $\delta^{18}\text{O}$  is recorded by the warm season species during July and August 1981, and the full range of  $\delta^{18}\text{O}$  for all species in June, July, and August samples exceeds 2‰. In contrast, samples from December through March have a spread of  $\delta^{18}\text{O}$  that is <1‰. The data are generally insufficient to reveal trends in stable isotope ratios as a function of test size. Notable exceptions are *G. sacculifera* (July and October 1981) and *G. bulloides*

(May 1982), which both show a clear increase in  $\delta^{13}\text{C}$  with size.

## 4. Discussion

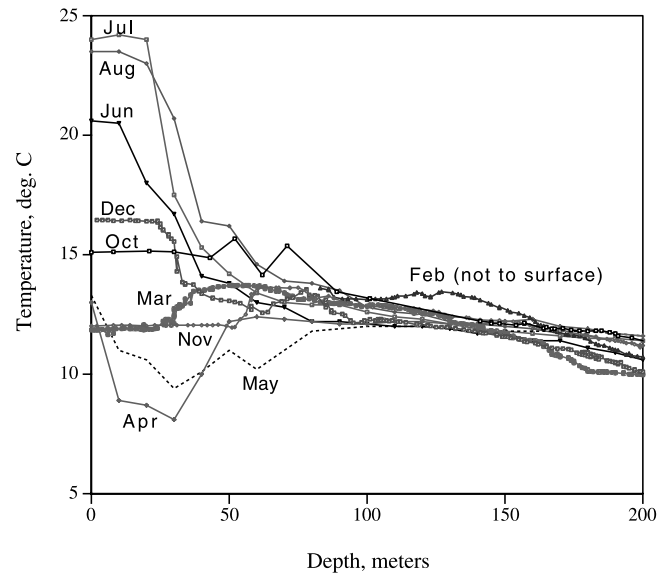
### 4.1. Faunal Distribution

[10] In the early 1960s, R. Cifelli [1962, 1965] participated in four seasonal cruises, during which he towed for planktonic foraminifera from 200 m to the surface using a 153  $\mu\text{m}$  net along a line from Woods Hole to Bermuda. This line went through the present study area, but each occupation of the line had only one or two stations in the 39°–40°N range, where we have many samples (Figure 1). Cifelli found that the shelf and upper slope were dominated by species of “*Globigerina*” (i.e., *Globigerina* and *Neogloboquadrina*) in all seasons, with reduced numbers but higher diversity and warmer fauna approaching the Gulf Stream. In the summer, *G. bulloides* and *N. pachyderma*

(dextral) (his *Globigerina incompta*) were dominant in our study area, and *G. inflata* was found in low to moderate abundances. In the fall, “*Globigerina*” was still about 60% of the fauna, with reduced abundance of *G. bulloides* and increased abundance of *G. inflata* and *N. pachyderma* (dextral). In addition to *G. bulloides* in the winter, he found increased *Turborotalia quinqueloba*, and by spring the fauna was about 80% *G. bulloides*.

[11] Cifelli’s [1962, 1965] results stand in strong contrast to the MOCNESS results presented here (Table 1) as well as those of Fairbanks *et al.* [1980]. As mentioned above, there are several reasons the faunal data presented here should not be taken quantitatively, but the large differences from Cifelli’s results may be meaningful. For example, our results suggest that *G. bulloides* was not present in the slope waters during the summer of 1981, and Fairbanks *et al.* [1980] found it to be uncommon in the generally warm and diverse fauna of 28 November 1975. Although this is a relatively fragile species, if it is absent from our samples because of preservation, then we would not expect to see other abundant and fragile species such as *Orbulina universa*, *G. ruber*, or pteropods. Cifelli did not state the size of his summer *G. bulloides* and *N. pachyderma* (dextral), but if they were as small as 150  $\mu\text{m}$ , we would expect to see some because we found numerous *G. ruber* and *G. sacculifera* in the 150–250  $\mu\text{m}$  size fraction despite the 333  $\mu\text{m}$  net size (Tables 1 and 2). Our relatively high abundances of *G. inflata* may be an artifact of the larger net used in most of the MOCNESS deployments, but *G. inflata* is also an important species in the 63  $\mu\text{m}$  samples of December 1981 and March 1982. Furthermore, *G. inflata* was also the most abundant of all species in the upper 100 m in November 1975 [Fairbanks *et al.*, 1980]. Other important differences are that we find *N. dutertrei* was very abundant in the summer (Cifelli said “scarce”), that *N. pachyderma* (dextral) was abundant only in the winter, and that we never found *T. quinqueloba*, even in the winter sampling with the 63  $\mu\text{m}$  net when pteropods indicate good preservation (9 February 1982 and 14 March 1982, Table 1).

[12] We do not have a completely satisfactory explanation for the differences among the planktonic foraminiferal fauna between Cifelli’s [1962, 1965] sampling and Wiebe’s [Miller *et al.*, 1991] of 15 and 20 years later, but they are large enough that they may not be sampling artifacts. Considering the dynamic nature of the slope water system, it is likely they may reflect real differences in water properties between the early 1960s and the early 1980s, especially in the winter. We can rule out the effect of warm core rings in our time series because an important reason for the BT profiling was to avoid them (although Fairbanks *et al.* [1980] sampled a warm core ring as well as the slope water station). The best support for the notion of real hydrographic differences comes from the analysis of Licandro *et al.* [2001]. These authors reconstructed a time series of copepod distributions in the Gulf of Maine for the years 1961–1991. Their results are relevant to ours because the Gulf of Maine is flushed by open ocean waters that pass over and around Georges Bank (Figure 1). Licandro *et al.* [2001] found that the abundance of the dominant year-round copepod *Calanus finmarchicus* anti-

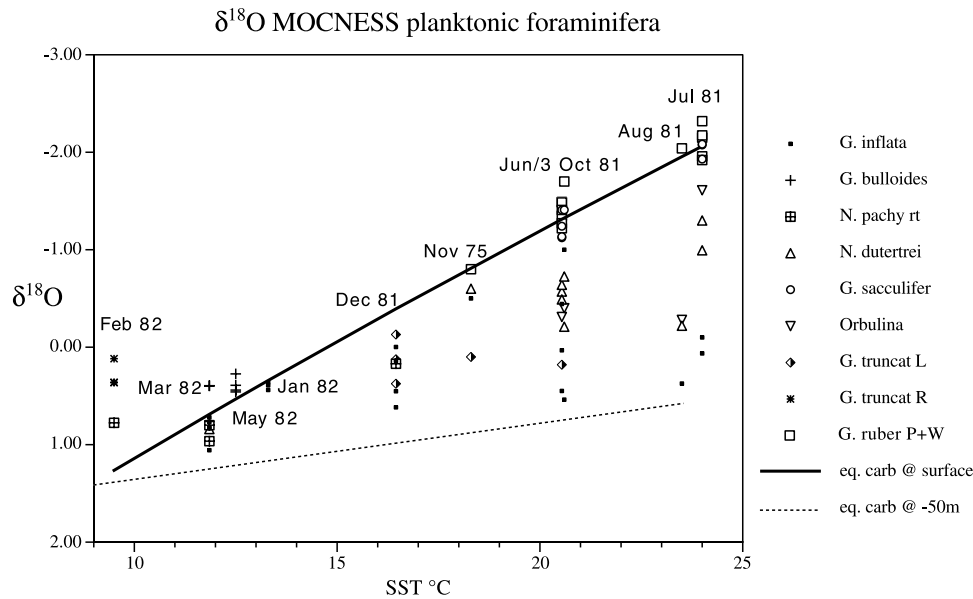


**Figure 3.** Bathythermograph profiles associated with MOCNESS deployments during the 1981–1982 time series. Compare the actual measurements to the climatology (Figure 2b).

correlated with the interannual trend of decreasing SST in the early 1960s. However, the monthly average SST data since 1960 near our tow sites do not show the summer of 1960 to be unusually cold, although it is easy to see how the strong winter cooling that culminated in the middle 1960s could have drawn down the interannual average SST used by Licandro *et al.* [2001] (Figure 2d). During those cold winters, which are associated with the negative phase of the North Atlantic Oscillation [Hurrell, 1995], a stronger Labrador Current probably brought colder surface waters to the south [Petrie and Drinkwater, 1993]. Winter SSTs well below 10°C off Cape Cod in the middle 1960s should have been cold enough to sustain a population of *N. pachyderma* (sinistral) and could easily account for Cifelli’s observations of *T. quinqueloba* in January and May 1961.

#### 4.2. Foraminiferal $\delta^{18}\text{O}$ as a Proxy for Upper Ocean Temperature off Cape Cod

[13] The slope waters off Cape Cod displayed an annual SST range of about 15°C as measured by BTs in 1981–1982 (Figure 3). With no pairs of in situ salinity and water isotope data it is impossible to calculate exactly the  $\delta^{18}\text{O}$  of calcite precipitated in equilibrium with seawater. However, climatology of the slope waters in the vicinity of most of the MOCNESS deployments shows that salinity changes little from winter to the summer (Figure 2a) and that the seasonal range of SST is similar to the BT measurements (Figure 2b). Using the North Atlantic  $\delta^{18}\text{O}$ -salinity relationship of Craig and Gordon [1965] ( $\delta^{18}\text{O}_{\text{water}} = 0.61(\text{salinity})$ ), the  $\sim 0.3\text{‰}$  difference in surface salinity between summer and winter could introduce a  $\delta^{18}\text{O}$  error of  $\sim 0.1\text{‰}$  in our calculations. Thus most of the variability in surface dwelling planktonic



**Figure 4.** Relationship between the  $\delta^{18}\text{O}$  of calcium carbonate secreted in equilibrium with ambient surface waters during the MOCNESS sampling used in this study and the  $\delta^{18}\text{O}$  measured in species of planktonic foraminifera. The dotted line approximates equilibrium precipitation of  $\text{CaCO}_3$  at 50 m based on the data in Figure 2c. Because of their scarcity (Table 1), *Globigerinita glutinata*, *Globigerinoides conglobatus*, and *Pulleniatina obliquiloculata* data (Table 2) are excluded. Note that except for February 1982, the lowest  $\delta^{18}\text{O}$  measured in each MOCNESS deployment is close to the expected equilibrium value. This suggests that throughout the year, there may always be a species living near the surface or in the surface mixed layer. Because there is little seasonal variability in sea surface salinity today (Figure 2a), the lowest  $\delta^{18}\text{O}$  measured in each MOCNESS is mostly a function of SST. November 1975 data come from Fairbanks *et al.* [1980].

foraminiferal  $\delta^{18}\text{O}$  in the study area must reflect SST variability. A similar situation exists in the Gulf of California, where the seasonal SST range is very large and there is little salinity change [Thunell *et al.*, 1999].

[14] On the other hand,  $\delta^{18}\text{O}$  variability below the surface reflects changes in both temperature and salinity in the slope waters. In the  $\sim 50$  m below the surface, temperatures decrease  $\sim 8^\circ\text{C}$  during the summer and increase  $\sim 2^\circ\text{C}$  in the winter (Figure 2b), yet salinity increases by nearly 1 practical salinity unit (psu) (Figure 2a). Thus, during summer months, there is a strong trend toward increasing  $\delta^{18}\text{O}$  with water depth and no increase during winter months (Figure 2c) [see also Fairbanks *et al.*, 1980]. This means that barring disequilibrium effects,  $\delta^{18}\text{O}$  of species growing in winter in the upper 100 m should all reflect winter SST and summer species should reflect their depth habitat.

[15] Figure 4 shows the relationship between foraminiferal  $\delta^{18}\text{O}$ , SST, and the calculated  $\delta^{18}\text{O}$  of calcite precipitated in isotopic equilibrium with sea surface conditions using the equation of Shackleton [1974]. Here we include the results of Fairbanks *et al.* [1980] for November 1975. It is evident that for nearly every MOCNESS the lowest  $\delta^{18}\text{O}$  is close to the line of equilibrium precipitation. This suggests that for nearly every month of the year, there is a species that may be living in or near the surface mixed layer and depositing its calcite close to isotopic equilibrium. The only exception to this generalization is in the February sample, when three

analyses of right-coiling *G. truncatulinoides* were about 1‰ lower than equilibrium.

[16] For paleoceanographic purposes the extent of  $\delta^{18}\text{O}$  disequilibrium is important. For example, although the summer species *G. ruber* and *G. sacculifera* are close to isotopic equilibrium in our samples, a difference of a few tenths per mil could translate to errors in SST reconstruction of  $>1^\circ\text{C}$ . Deuser and Ross [1989] showed that *G. ruber* (white) is lower than equilibrium by about 0.2‰, and Fairbanks *et al.* [1980] calculated that spinose species are a few tenths per mil lower than equilibrium. The November 1975 data of Fairbanks *et al.* [1980] may lie below our equilibrium line (Figure 4) because we used different paleotemperature equations and different salinity- $\delta^{18}\text{O}$  relationships. Nevertheless, the data display an overall consistency that leads to a few conclusions.

[17] First, as is well known from many other locations, the  $\delta^{18}\text{O}$  of *G. ruber* and *G. sacculifera* probably best represent summer SST. As Be and Tolderlund [1971] and Deuser and Ross [1989] showed, the pink variety of *G. ruber* flourishes in the summertime and probably reflects the warmest SST. If we assume that the flux (mass accumulation rate) of this species reaches a maximum sometime between June and October, when we observe a 0.75‰ range in  $\delta^{18}\text{O}$  (Figure 4), then the oxygen isotope method could underestimate SST by as much as  $3^\circ\text{C}$ . If the Fairbanks *et al.* [1980] result for late November is typical, then this discrepancy could be even larger.

[18] Second, we do not have clear evidence for a species that adequately represents winter SST. *N. pachyderma* (dextral) is a good candidate, but it is small and may be underrepresented in these samples, and among its three occurrences (December, February, and March) it does not have the lowest  $\delta^{18}\text{O}$ . The unusually low  $\delta^{18}\text{O}$  of *G. truncatulinoides* (right-coiling) in February 1982 may be anomalous because this species is usually considered to be a thermocline or deep dweller [Hemleben et al., 1985; Lohmann, 1995; LeGrande et al., 2004] and is sometimes found to be isotopically heavier than equilibrium in deep tow samples (i.e., living at or below the thermocline [Fairbanks et al., 1980]). In their study of trap and tow samples from the Sargasso Sea, Hemleben et al. [1985] found that juvenile *G. truncatulinoides* have lower  $\delta^{18}\text{O}$  than adults and that adults are on average 0.25–0.5‰ lower than equilibrium. If the slope water samples are similar, then large surface dwellers that have not yet added calcite in colder (deep) waters may have a disequilibrium effect that is even greater than 0.5‰. *G. bulloides* is isotopically light, as Fairbanks et al. [1980] found for other spinose species, and is only abundant in the spring (March and May). At those times, SST is still close to its late winter minimum, so this species has potential to be developed as a winter SST proxy. In the Sargasso Sea, *G. inflata* is known to have the greatest flux during late winter when the mixed layer is cold and deep [Deuser and Ross, 1989]. It is a good proxy for winter SST in those waters, but in the slope waters this species is abundant throughout the year. There its  $\delta^{18}\text{O}$  is much greater than most other species from June to October. Equilibrium calculations based on climatology (Figure 2c) suggest that *G. inflata* may live at 50 m during summer in the slope waters (Figure 4).

[19] Finally, if planktonic foraminifera are depth or density stratified, as is commonly believed [Fairbanks et al., 1980; Lohmann, 1995], then the  $\delta^{18}\text{O}$  of winter species should cluster and the  $\delta^{18}\text{O}$  of warm season species should display a range about equal to the annual range of SST. This is approximately what is observed (Figure 4) and reflects the thick mixed layer (Figure 3)

and the fact that increasing salinity with water depth cancels out the isotope effect of increasing temperature (Figure 2). It is likely that in a mixed assemblage of planktonic foraminifera from sediments beneath the slope waters the range of  $\delta^{18}\text{O}$  among all species will represent the seasonal range of SST.

## 5. Conclusions

[20] A monthly series of plankton tows from 1981 to 1982 in the slope waters off Cape Cod shows the seasonal succession of planktonic foraminifera. The fauna is warm and diverse from June through October, with prominent tropical/subtropical species such as *G. ruber*, *G. sacculifera*, *N. dutertrei*, and *Orbulina universa*. The November–May fauna includes *G. bulloides* and *N. pachyderma* (dextra), but the data are not sufficient to determine if these species are always present during the cold months or if one succeeds the other. *G. inflata* occurs throughout the year.

[21] The seasonal range of oxygen isotope ratios closely follows the annual SST range of nearly 15°C. In the summer months, *G. ruber* is isotopically lightest, with  $\delta^{18}\text{O}$  close to equilibrium. Likewise, *G. bulloides* and *N. pachyderma* (dextral) have  $\delta^{18}\text{O}$  nearly in equilibrium with surface waters in the winter and spring. Because salinity of surface waters does not change appreciably during the year, the large seasonality of SST dominates the  $\delta^{18}\text{O}$  of surface dwelling foraminifera. Thus  $\delta^{18}\text{O}$  of pairs of winter and summer species can be used to determine the seasonal extremes of SST in paleorecords from the slope waters, provided the salinity- $\delta^{18}\text{O}$  relationship does not change.

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