

The glacial/interglacial temperature range of the surface water of the oceans at low latitudes

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Abstract—The isotopic and micropaleontological evidence pertinent to the glacial/interglacial temperature range of the surface water of the ocean at low latitudes is reassessed. We conclude that the maximum range is 7.8°C in the Caribbean-equatorial Atlantic, 5.5°C in the northern Indian Ocean, and 3.6°C in the equatorial Pacific. The intertropical, area-weighted average is 5.0°C. The negligible range reported by CLIMAP may be due to faulty calibration.

INTRODUCTION

EARLY ISOTOPIC AND micropaleontological work (EMILIANI, 1955; ERICSON and WOLLIN, 1956) demonstrated a large isotopic and micropaleontological change between the hypsithermals and bathythermals of the Late Quaternary. Since then much work has been done in an attempt to reconstruct the true history of the ice ages (see review by MIX, 1987). Different methods and different interpretations have produced conclusions that are at variance with each other. This disagreement requires scrutiny.

THE ISOTOPIC EVIDENCE

The isotopic evidence, graphically summarized by BROECKER (1986, Figs. 1 and 2), is reported in Table 1. We notice that the benthic foraminifera give similar $\delta^{18}\text{O}$ values (1.6–1.8) around the world, while the planktic foraminifera exhibit marked variations from region to region. SHACKLETON (1967) and SHACKLETON and OPDYKE (1973), assuming that the bottom temperature in the ocean remained constant during the Quaternary, assigned the entire isotopic range measured on benthic foraminifera to the change in isotopic composition of the ocean water related to glaciation. This would require the equatorial Pacific to have been warmer during the ice ages than during the interglacial ages. Evidence now indicates that bottom water temperature did not remain constant. Table 2 shows that there has been a decrease of 1–2°C in the bottom

temperature of the world ocean since the last hypsithermal.

The world ocean bottom water consists of a mixture of the warmer (2.5°C), more saline (34.9 per mil) North Atlantic deep water and the colder (–0.5°C), less saline (34.6 per mil) Antarctic bottom water. During interglacial ages, bottom water consists mainly of North Atlantic deep water, while it may consist mainly of Antarctic bottom water during glacial ages. If so, the observed temperature decrease of 1–2°C in the bottom water of the world ocean (Table 2) may herald the initiation of the next ice age.

The temperature changes of the bottom water between the hypsithermals and bathythermals of the Quaternary were considerably larger, amounting to 5.7°C in the Atlantic, 3.8°C in the Indian Ocean, and 2.7°C in the equatorial Pacific (LABEYRIE *et al.*, 1987). These data, together with the isotopic data of Table 1, would indicate a surface temperature change of 5.6°C in the Caribbean-equatorial Atlantic, 3.9°C in the northern Indian Ocean, and 2.6°C in the eastern equatorial Pacific. The actual surface temperature change, however, may have been even larger. ANDERSON and STEINMETZ (1981), in fact, showed that coccoliths in a Caribbean core exhibit a glacial/interglacial isotopic range of 2.8 per mil, which is 40% greater than that given by the shallow planktic foraminiferal species *Globigerinoides rubra* and *Globigerinoides sacculifera*. The ratios of the isotopic compositions of different foraminiferal species to each other remain approximately constant worldwide. If the ratio of the isotopic composition of the coccoliths to that of *G. rubra* and *G. sacculifera* also remained constant, the glacial/interglacial temperature change could

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Table 1. Oxygen isotopic change ($\delta^{18}\text{O}$ in per mil relative to PDB-1) between bathythermal 2 and hypsithermal 1 (data from BROECKER, 1986)

Region	Foraminifera	
	Planktic	Benthic
North Atlantic	1.7–2.4	1.8
Caribbean	1.9–2.1	1.8*
Equatorial Atlantic	1.6–1.8	1.6–1.8
South Atlantic	1.1–1.6	1.6–1.7
Northern Indian Ocean	1.5–2.1	1.8
Eastern Equatorial Pacific	1.1–1.5	1.6–1.8
Western Equatorial Pacific	1.0–1.2	—

* Inferred from the adjacent equatorial Atlantic.

have been 40% greater than that given by *G. rubra* and *G. sacculifera*, or 7.8°C in the Caribbean-equatorial Atlantic, 5.5°C in the northern Indian Ocean, and 3.6°C in the equatorial Pacific.

Coccolithophoridae do not deposit their calcite in isotopic equilibrium with ambient sea water. Isotopic disequilibrium for the five species used by ANDERSON and STEINMETZ (1981) amounts to +1 per mil and is not affected by downcore changes in the relative abundances of the five species (four *Gephyrocapsa* and one *Syracosphaera*). As observed in other taxa (benthic foraminifera, echinoderms, corals, etc.), the disequilibrium effect is constant and independent of temperature. Because disequilibrium does not change with changing temperature (cf. DUDLEY *et al.*, 1986, Figs. 1 and 2), the glacial/interglacial isotopic range measured by ANDERSON and STEINMETZ (1981) is real and has an important bearing on the actual glacial/interglacial temperature range of the surface seawater at low latitudes.

Coccolithophoridae occur most abundantly in

the top 50 m of ocean water. Most are eurythermal. Reproduction is rapid (one to two cell divisions per day). While some taxa (e.g. *Umbellosphaera*) exhibit seasonality even at subtropical latitudes (OKADA and MCINTYRE, 1979), *Gephyrocapsa* (which is the most abundant taxon in the core studied by ANDERSON and STEINMETZ, 1981) and *Syracosphaera* do not (see OKADA and MCINTYRE, 1979, Fig. 7). Planktic foraminifera, on the other hand, exhibit marked seasonality at subtropical and higher latitudes, with *Globigerinoides rubra* as a dominant summer species (TOLDERLUND and BÉ, 1971; WILLIAMS *et al.*, 1981). At low latitudes where the temperature difference between the warmer and the colder times of the year is a few degrees centigrade at most, *Globigerinoides sacculifera* appears to prefer the warmer season, while *G. rubra* exhibits no apparent seasonality (Table 3).

It is likely that during the ice ages the temperature difference between the warmer and colder seasons at low latitudes was more pronounced than today. If so, planktic foraminifera, especially *G. rubra* and *G. sacculifera* which occupy a shallow habitat, may have developed a stronger seasonality and deposited their shells predominantly during the warmer portion of the year. A reduction in the amplitude of the glacial/interglacial isotopic signal to the values listed in Table 1 would result.

THE NON-ISOTOPIC EVIDENCE

The glacial/interglacial surface temperature range can also be assessed by using temperature tolerance limits. The species *Globorotalia menardii*, *Pulleniatina obliquiloculata*, and *Sphaeroidinella dehiscens* have sharply restricted temperature tolerance limits (Table 4) and are, therefore, particularly useful. These are deeper water species that repro-

Table 2. Temperature decrease of the bottom water of the ocean since the last hypsithermal. Water corrections from CRAIG and GORDON (1965). The isotopic temperatures were calculated using the revised Epstein equation published by YAPP (1979). Data from the following references: (1) DUPLESSY *et al.* (1975); (2) DUPLESSY *et al.* (1980); (3) STREETER and SHACKLETON (1979); (4) RUDDIMAN and MCINTYRE (1971); (5) SHACKLETON (1974); (6) DUPLESSY (1978)

Genus	Location	Depth (m)	$\delta^{18}\text{O}$ (per mil)	Taxonomic corr. (per mil)	Water corr. (per mil)	$\delta^{18}\text{O}$ (corrected)	Isotopic temp. (°C)	Ambient temp. (°C)	Temp. decrease (°C)	Ref.
<i>Cibicides</i>	Norwegian-Greenland Sea	1668–3139	+3.88	+0.64	+0.1	4.42	0.4	-1.4	1.2	(1)
<i>Cibicides</i>	54°38'N 16°21'W	2209	+2.59	+0.64	+0.1	3.13	4.5	3.3	1.2	(2)
<i>Uvigerina</i>	44°01'N 24°32'W	3331	+3.00	0.00	+0.1	2.90	5.3	2.8	2.5	(3)
<i>Uvigerina</i>	41°00'N 32°55'W	3371	+3.22	0.00	+0.1	3.12	4.6	2.8	1.8	(4)
<i>Uvigerina</i>	47°01'N 129°34'W	2650	+3.35	0.00	-0.2	3.55	3.1	1.3	1.8	(5)
<i>Uvigerina</i>	47°31'S 79°52'E	3193	+3.52	0.00	-0.2	3.72	2.6	0.8	1.8	(5)
<i>Nonion</i>	43°49'S 51°19'E	3284	+3.13	+0.34	-0.2	3.67	2.7	0.6	2.1	(6)

Table 3. Seasonal distribution of *G. rubra* and *G. sacculifera* in the equatorial Atlantic (data from JONES, 1967)

Season	Surface temperature (°C)	Surface salinity (per mil)	Max. standing crop (no. of individuals per 1000 m ³ of seawater)	
			<i>G. rubra</i>	<i>G. sacculifera</i>
September	25–26	35.0–35.7	6000	10,000
April–May	27–29	34.8–35.6	4000–7000	15,000–30,000

duce near the surface during the winter (DEUSER *et al.*, 1981; WILLIAMS *et al.*, 1981). Because shell deposition begins near the surface (EMILIANI, 1971; WILLIAMS *et al.*, 1981), a species would disappear if surface winter temperature drops below the threshold for reproduction and initial shell growth of that species. Table 5 shows the depth at which temperature is 18.5°C, together with the relative abundances of *G. menardii* and temperature data. As may be seen, the 18.5°C isothermal surface deepens from east to northwest in the equatorial Atlantic, reaching its maximum depth in the Caribbean. DURAZZI (1981) showed that the minimum isotopic depth of *G. menardii* exhibits the same trend.

The absence of *Globorotalia menardii*, *Pulleniatina obliquiloculata*, and *Sphaeroidinella dehiscens* from the equatorial-tropical Atlantic and the Caribbean during the last ice age (ERICSON and WOLLIN, 1956) indicates that winter temperature dropped below 18.5°C, a decrease of at least 7°C for the equatorial-tropical Atlantic and about 8°C for the Caribbean.

Some species that grow during the summer at high northern latitudes become winter species at lower latitudes. A conspicuous example is *Globigerina bulloides* (TOLDERLUND and BÉ, 1971, Figs. 4 and 5). Other species remain summer species but disappear when summer temperature is too high. *Globigerina quinqueloba*, a typical summer species in the northern North Atlantic (TOLDERLUND and BÉ, 1971), is not found if summer temperature is higher than 22°C (PHLEGER *et al.*, 1953, Table 38; KIPP, 1976, Fig. 5). This species can be used to assess the glacial/interglacial range of summer surface temperature. Because *G. quinqueloba* is present during bathythermal 2 in equatorial Atlantic core 246 (PHLEGER *et al.*, 1953, Table 17; *cf.* with EMILIANI, 1955, Fig. 6), we conclude that summer temperature in the equatorial Atlantic at that time was lower than 22°C, indicating a drop of at least 4.5°C.

In the equatorial Pacific, *Globorotalia menardii* and *Pulleniatina obliquiloculata* remain abundant downcore (10 to 40% and 5 to 20%, respectively—

see ARRHENIUS, 1952, Appendix, plates 2.58–2.62). This indicates that winter temperature did not drop below 18.5°C in the eastern equatorial Pacific. Present surface temperature ranges from 25 to 27°C in the area of the cores described by Arrhenius. *Sphaeroidinella dehiscens* is present mainly in interglacial times, indicating that temperature may have dropped below 23°C in glacial times. A glacial/interglacial range of >3°C is thus suggested. Table 6 shows the temperature change from bathythermal 2 to hypsithermal 1 based on oxygen isotope analysis of planktic foraminifera (increased by 1.4 to account for the coccolith evidence) and on the temperature tolerances of stenothermal species.

A PROBLEM WITH CLIMAP?

CLIMAP (1976, 1981) determined the relative abundances (percentages) of planktic foraminifera in a large number of gravity and piston core tops, and related these percentages to the temperature prevailing at the surface. Having thus calibrated the composition of the core-top foraminiferal faunas, CLIMAP determined the faunal composition in core samples below the tops, dating from bathythermal 2 (18,000 y BP), and proceeded to reconstruct temperature conditions at that time. Their reconstructions showed that “large areas of the tropics and subtropics within all oceans had sea-surface temperatures as warm as, or slightly warmer, than today” (CLIMAP, 1981, p. 9). Similar conclusions, with some notable regional exceptions, were reached by PRELL (1985). These conclusions

Table 4. Temperature tolerance limits for three species of planktic foraminifera (data from PHLEGER *et al.*, 1953; KIPP, 1976)

Species	Lowest tolerable temperatures (°C)	
	Winter	Summer
<i>Globorotalia menardii</i>	18.5	22.5
<i>Pulleniatina obliquiloculata</i>	18.5	22.5
<i>Sphaeroidinella dehiscens</i>	23.0	26.0

Table 5. Percentages of *Globorotalia menardii* in CLIMAP's core top samples between latitudes 2°S and 23°N in the Atlantic. Samples 52 and 56 are not included here because below the R_0 level of VINCENT and BERGER (1981, p. 1087). Data from IMBRIE and KIPP (1971)

Sample No.	Core No.	Lat.	Long.	Depth (m)	% of <i>G. menardii</i>	Surface seasonal temp. range (°C)	Subsurface temp. (°C)		Depth at which temp. = 18.5°C
							100 m	200 m	
42	V22-204	15°01'N	23°14'W	1723	9.2	21.5-26.5	15.5	17.5	70
44	V10-89	23°02'N	43°48'W	3523	1.1	23.0-26.0	21.9	18.5	190
45	V12-79	1°31'S	11°47'W	3823	5.4	23.3-26.0	16.0	12.5	110
48	A180-72	0°36'N	21°47'W	3841	6.9	24.0-27.5	21.1	12.5	110
49	V16-21	17°17'N	48°25'W	3975	0.9	24.5-27.0	23.0	16.0	190
50	A180-76	0°46'S	26°02'W	3512	5.4	25.0-27.0	22.5	12.5	120
53	V14-5	0°51'N	32°51'W	3255	7.8	26.0-27.0	24.0	12.0	130
57	V20-230	1°57'S	39°02'W	3294	1.3	26.0-27.5	25.5	12.0	145
58	V20-7	11°33'N	60°31'W	1018	3.1	26.0-27.5	24.0	14.5	180
59	V20-234	5°19'N	33°02'W	3133	3.6	26.5-27.0	22.5	12.0	200
60	V18-21	4°14'N	47°45'W	2374	12.4	26.5-27.0	26.5	12.0	150
61	V12-122	17°00'N	74°24'W	2800	7.5	26.5-28.0	25.5	16.0	210

are in disagreement with both the isotopic and the nonisotopic evidence discussed above, suggesting that there may be a problem with CLIMAP.

The problem may derive from faulty calibration. All core top samples used for calibration were verified to be Holocene in age by the usage of micropaleontological criteria (IMBRIE and KIPP, 1971). At latitudes below 20° in the North Atlantic and the Caribbean, the Holocene (Ericson's Zone Z) is characterized by the presence of *Globorotalia menardii* which, in modern sediments, comprises more than 5% of the planktic foraminiferal fauna (PHLEGER *et al.*, 1953, p. 62, Fig. 14; BERGER *et al.*, 1985, Tables 4A and 4B). Table 7 shows the relative abundance of *G. menardii* in deep-sea cores from the Caribbean and the tropical-equatorial Atlantic that have been accurately analyzed both isotopically (EMILIANI, 1955; IMBRIE *et al.*, 1973; BERGER *et al.*, 1985) and micropaleontologically (PHLEGER *et al.*, 1953; IMBRIE and KIPP, 1971; BERGER *et al.*, 1985). The modern age of the core top is assured and, in all cases except one, *G. menardii* is more than 5% (Table 7). The single exception, core INMD-97 with 4.0% of *G. menardii* at the top, shows, however, 6% of *G. menardii* 4-5 cm below top (last hypsithermal).

When cores from the equatorial Atlantic-Caribbean region are analyzed micropaleontologically,

the percentage of *G. menardii* is seen to drop rapidly from more than 5% at or near the top of Zone Z to 0 at the bottom. Because of the steepness of the micropaleontological and isotopic gradients through Zone Z, the absence (by local submarine erosion) or loss (by coring) of even a few centimeters at the top coupled with bioturbation will produce an assemblage that still contains *G. menardii* and, therefore, belongs to Zone Z by definition, yet is not representative of hypsithermal or even modern conditions (modern surface temperatures in the Caribbean-equatorial Atlantic region are about 1°C cooler than during hypsithermal 1—see EMILIANI, 1955, Figs. 7-9). Indeed, 5 out of the 11 Atlantic core tops located between the equator and the tropic and used by IMBRIE and KIPP (1971) for their CLIMAP calibration contain less than 5% of *G. menardii* (Table 5). This indicates that the corresponding faunas were not related to the present surface temperatures, but to the lower temperature obtaining during earlier Holocene or even late Pleistocene times. In higher latitudes and in regions of upwelling, where the sedimentation rates are higher, this problem is less acute and the CLIMAP temperatures are probably closer to reality.

CONCLUSION

We conclude that temperature during the last bathythermal was 8°C colder than during the last

Table 6. Bathythermal/hypsithermal temperature range (°C) of the surface water of the ocean

Method	Caribbean	Eq. Atlantic	N. Indian	Eq. Pacific
Isotopes	7.8	7.8	5.5	3.6
Temp. tolerances	>8	>7	—	>3

Table 7. Percentage of *Globobulimina menardii* at the top of Caribbean core V12-122, tropical-equatorial Atlantic box cores (INMD-97 through INMD-115), and equatorial Atlantic piston core 246. Data from the following references: (1) IMBRIE and KIPP (1971); (2) BERGER *et al.* (1985); (3) PHLEGER *et al.* (1953)

Core No.	Lat.	Long.	Depth (m)	Thickness of Zone Z (cm)	% of <i>G. menardii</i> at top of core	Ref.
V12-122	17°00'N	74°24'W	2800	40	7.5	(1)
INMD-97	16°39'N	46°08'W	3619	21	4.0	(2)
INMD-101	6°57'N	26°27'W	4093	21	10.0	(2)
INMD-104	4°15'N	21°55'W	3279	25	11.7	(2)
246	0°48'N	31°28'W	3210	30	8.0	(3)
INMD-109	5°27'S	15°58'W	3895	>31	17.3	(2)
INMD-110	10°02'S	13°23'W	1959	23	10.0	(2)
INMD-111	12°39'S	13°51'W	3069	14	13.0	(2)
INMD-113	15°15'S	14°58'W	3471	16	5.0	(2)
INMD-115	17°38'S	16°13'W	3427	14	6.7	(2)

hypsithermal in the Caribbean-equatorial Atlantic, 5.5°C colder in the northern Indian Ocean, and 3.6°C colder in the equatorial Pacific. The inter-tropical, area-weighted average is 5.0°C. This value is identical to that obtained by RIND and PETEET (1985), who reviewed the non-isotopic evidence from low latitudes and simulated climate during bathythermal 2 using model II of HANSEN *et al.* (1983). In order to reproduce the observed snowline depressions at low latitudes and the widespread tropical aridity evidenced by pollen analysis, they had to lower the mean surface temperature of the ocean by 5–6°C. MIX and PISIAS (1988) stress that cooling of the deep ocean during the glacial ages implies a stronger thermohaline circulation. Indeed, increased vertical circulation with a doubling of the coccolith and foraminiferal productivity, was demonstrated by BROECKER *et al.* (1958) for the Atlantic and by ARRHENIUS (1952) for the Pacific.

We believe that the CLIMAP data base should be recalibrated using box cores instead of gravity or piston core tops and that the truly modern age of the tops be assessed by either oxygen isotope analysis at one cm intervals (as in EMILIANI, 1955, Figs. 8–10) or by accelerator ¹⁴C dating, or both. The fact that different taxonomic groups (foraminifera, radiolaria, coccolithophoridae) give concordant, even though inaccurate, surface temperatures when subjected to the Imbrie-Kipp method of analysis (MOLFINO *et al.*, 1982) strengthens the need for recalibration. CLIMAP's data base could then be reanalyzed using the method advocated by MALMGREN and KENNETT (1976, 1978) which, according to them, is more sensitive to variations in the significant, stenothermal and stenohaline species. LIDZ (1966) showed that the micropaleontological signal can be amplified if ratios of warm to

cold steno species are used. Perhaps this technique too could be incorporated in the new analysis.

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REFERENCES

- ANDERSON T. F. and STEINMETZ J. C. (1981) Isotopic and biostratigraphical records of calcareous nannofossils in a Pleistocene core. *Nature* **294**, 740–744.
- ARRHENIUS G. (1952) Sediment cores from the East Pacific. *Swedish Deep-Sea Exped. 1947–1948, Repts., Vol. 5, Fasc. 1* (with Appendix).
- BERGER W. H., KILLINGLEY J. S., MELTZER C. V. and VINCENT E. (1985) Two-step deglaciation: ¹⁴C-dated high-resolution $\delta^{18}\text{O}$ records from the tropical Atlantic Ocean. *Quatern. Res.* **23**, 258–271.
- BROECKER W. S. (1986) Oxygen isotope constraints on surface ocean temperatures. *Quat. Res.* **26**, 121–134.
- BROECKER W. S., TUREKIAN K. K. and HEEZEN B. C. (1958) The relation of deep-sea sedimentation rates to variations in climate. *Amer. J. Sci.* **256**, 503–517.
- CLIMAP PROJECT MEMBERS (1976) The surface of the ice-age earth. *Science* **191**, 1131–1137.
- CLIMAP PROJECT MEMBERS (1981) Seasonal reconstructions of the earth's surface at the last glacial maximum. *Geol. Soc. Amer. Map and Chart Ser., MC-36*.
- CRAIG H. and GORDON L. I. (1965) Deuterium and oxygen-18 variations in the ocean and the marine atmosphere. In *Stable Isotopes in Oceanographic Studies and Paleotemperatures* (ed. E. TONGIORGI), pp. 9–130. Consiglio Nazionale delle Ricerche, Laboratorio di Geologia Nucleare, University of Pisa, Italy.
- DEUSER W. G., ROSS E. H., HEMLEBEN C. and SPINDLER M. (1981) Seasonal changes in species composition, numbers, mass, size, and isotopic composition of planktonic Foraminifera settling into the deep Sargasso Sea. *Paleogeogr. Palaeoclim. Palaeoecol.* **33**, 103–127.
- DUDLEY W. C., BLACKWELDER P., BRAND L. and DU-

- PLESSY J.-C. (1986) Stable isotopic composition of coccoliths. *Mar. Micropaleontol.* **10**, 1–8.
- DUPLESSY J.-C. (1978) Isotope studies. In *Climatic Change* (ed. J. GRIBBIN), pp. 46–67. Cambridge University Press.
- DUPLESSY J.-C., CHENOUARD L. and VILA F. (1975) Weyl's theory of glaciation supported by isotopic study of Norwegian core K 11. *Science* **288**, 1208–1209.
- DUPLESSY J.-C., MOYES J. and PUJOL C. (1980) Deep water formation in the North Atlantic during the last ice age. *Nature* **286**, 479–482.
- DURAZZI J. T. (1981) Stable-isotope studies of planktonic foraminifera in North Atlantic core tops. *Palaeogeogr. Palaeoclim. Palaeoecol.* **33**, 157–172.
- EMILIANI C. (1955) Pleistocene temperatures. *J. Geology* **63**, 538–578.
- EMILIANI C. (1971) Depth habitats and growth stages of pelagic foraminifera. *Science* **173**, 1122–1124.
- ERICSON D. B. and WOLLIN G. (1956) Correlations of six cores from the equatorial Atlantic and the Caribbean. *Deep-Sea Res.* **3**, 104–125.
- HANSEN J., RUSSELL G., RIND D., STONE P., LACIS A., LEBEDEFF S., RUEDY R. and TRAVIS L. (1983) Efficient three-dimensional global models for climate studies, models I and II. *Monthly Weather Rev.* **111**, 609–662.
- IMBRIE J. and KIPP N. G. (1971). A new micropaleontological method for quantitative paleoclimatology: application to a Late Pleistocene core. In *The Late Cenozoic Glacial Ages* (ed. K. K. TUREKIAN), pp. 71–181. Yale University Press.
- IMBRIE J., VAN DONK J. and KIPP N. G. (1973) Paleoclimatic investigation of a late Pleistocene Caribbean core: comparison of isotopic and faunal methods. *Quat. Res.* **3**, 10–38.
- JONES J. I. (1967) Significance of distribution of planktonic foraminifera in the equatorial Atlantic undercurrent. *Micropaleontol.* **13**, 489–501.
- KIPP N. G. (1976) New transfer function for estimating past sea-surface conditions from sea-bed distribution of planktonic foraminiferal assemblages in the North Atlantic. *Geol. Soc. Amer. Mem.* **145**, p. 3–41.
- LABEYRIE L. D., DUPLESSY J. C. and BLANC P. L. (1987) Variations in the mode of formation and temperature of oceanic deep waters over the past 125,000 years. *Nature* **327**, 477–482.
- LIDZ L. (1966) Deep-sea Pleistocene biostratigraphy. *Science* **154**, 1448–1452.
- MALMGREN B. A. and KENNETT K. P. (1976) Principal component analysis of Quaternary planktic Foraminifera in the Gulf of Mexico: paleoclimatic applications. *Mar. Micropaleontol.* **1**, 299–306.
- MALMGREN B. A. and KENNETT J. P. (1978) Test size variation in *Globigerina bulloides* in response to Quaternary palaeoceanographic changes. *Nature* **275**, 123–124.
- MIX A. C. (1987) The oxygen-isotope record of glaciation. In *The Geology of North America; Vol. K-3, North America and Adjacent Oceans during the Last Deglaciation*, (eds. W. F. RUDDIMAN and H. E. WRIGHT JR.), pp. 111–135. Geological Society of America, Boulder, Colorado.
- MIX A. C. and PISIAS N. G. (1988) Oxygen isotope analyses and deep-sea temperature changes: implications for rates of oceanic mixing. *Nature* **331**, 249–251.
- MOLFINO B., KIPP N. G. and MORLEY J. J. (1982) Comparison of foraminiferal, coccolithophorid, and radiolarian paleotemperature equations: assemblage coherency and estimate concordancy. *Quat. Res.* **17**, 279–313.
- OKADA H. and MCINTYRE A. (1979) Seasonal distribution of modern coccolithophores in the western North Atlantic Ocean. *Mar. Biol.* **54**, 319–329.
- PHLEGER F. B., PARKER F. L. and PEIRSON J. F. (1953) North Atlantic foraminifera. *Swedish Deep-Sea Exped. 1947–1948, Repts., Vol. 7, Fasc. 1*.
- PRELL W. L. (1985) The stability of low-latitude sea-surface temperatures: an evaluation of the CLIMAP reconstruction with emphasis on the positive SST anomalies. *U.S. Dept. Energy, Tech. Rept. 25*.
- RIND D. and PETEET D. (1985) Terrestrial conditions of the last glacial maximum and CLIMAP sea-surface temperature estimates: are they consistent? *Quat. Res.* **24**, 1–22.
- RUDDIMAN W. F. and MCINTYRE A. (1971) Oceanic mechanisms for the amplification of the 23,000-year ice volume cycle. *Science* **212**, 617–627.
- SHACKLETON N. J. (1967) Oxygen isotope analyses and Pleistocene temperatures reassessed. *Nature* **215**, 15–17.
- SHACKLETON N. J. (1974) Attainment of isotopic equilibrium between ocean water and the benthonic foraminiferal genus *Uvigerina*: isotopic changes in the ocean during the last glacial. *Coll. Intern. CNRS* **219**, 203–209.
- SHACKLETON N. J. and OPDYKE N. D. (1973) Oxygen isotope and paleomagnetic stratigraphy of equatorial Pacific core V28-238: oxygen isotopes temperatures and ice volumes on a 10⁵ and 10⁶ year scale. *Quat. Res.* **3**, 39–55.
- STREETER S. S. and SHACKLETON N. J. (1979) Paleocirculation of the deep North Atlantic: a 150,000 year record of benthic foraminifera and $\delta^{18}\text{O}$. *Science* **203**, 168–171.
- TOLDERLUND D. S. and BÉ A. W. H. (1971) Seasonal distribution of planktonic foraminifera in the western North Atlantic. *Micropaleontol.* **17**, 297–329.
- VINCENT E. and BERGER W. H. (1981) Planktonic Foraminifera and their use in paleoceanography. In *The Oceanic Lithosphere* (ed. C. Emiliani), pp. 1025–1119. John Wiley & Sons, New York.
- WILLIAMS D. F., BÉ A. W. H. and FAIRBANKS R. G. (1981) Seasonal stable isotopic variations in living planktonic foraminifera from Bermuda plankton tows. *Palaeogeogr. Palaeoclim. Palaeoecol.* **33**, 71–102.
- YAPP C. J. (1979) Oxygen and carbon isotope measurements of land snail shell carbonate. *Geochim. Cosmochim. Acta* **43**, 629–635.