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RECONSTRUCTING TROPICAL ATLANTIC HYDROGRAPHY USING PLANKTONTIC FORAMINIFERA AND AN OCEAN MODEL

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Abstract. In the tropical Atlantic, planktonic foraminfera species are vertically distributed with highest abundances occurring in the photic zone (approximately 0-100 m). The tropical Atlantic thermocline dips from east to west and varies seasonally due to changes in the southeast and northeast trade winds. In the east, the thermocline is in the photic zone, and in the west, the well-mixed surface layer extends below the photic zone most of the year. As expected from species vertical distributions in plankton tows, the species assemblages on the seafloor are correlated to the hydrographic conditions of the overlying surface ocean layer. A new technique to reconstruct past tropical Atlantic (20°N to 20°S) photic zone hydrography and surface wind field uses faunal assemblage data from deep-sea cores. Planktonic foraminifera abundances in core tops correlate with observations of modern photic zone hydrography defined here as seasonal temperature variation and mixed layer depth. The hydrography is mathematically described using empirical orthogonal function (EOF) analysis of annual temperature range as a function of depth. Factor analysis of 29 species of planktonic foraminifera from 118 core tops produces three factors. The factors correlate to mixed layer depth and the two EOF modes. The ocean model of the Atlantic ocean produces similar map patterns of the EOF modes. Therefore the model can be used to simulate hydrographic changes to compare with faunal predicted past hydrographic changes. Since the ocean model is wind driven, this approach provides a way of evaluating the validity of estimates of past wind stress changes and the contribution of these changes to the faunal changes in the past. A double wind stress run indicates that the central and eastern equatorial and southeast regions of the study area are most sensitive to wind stress increases. Factor analysis of the foraminifera abundances from the last glacial maximum (LGM) shows that species associations change downcore and demonstrates how the methods developed in this study can be applied. Comparison of the double wind stress experiment and the LGM faunal changes indicates some areas of significant agreement suggesting that faunal changes may reflect thermocline structure response to the LGM wind field. Discrepancies may reflect the fact that uniform changes in the north and south trade wind strengths did not occur at the LGM.

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INTRODUCTION

General circulation models (GCMs) predict increased northeasterly trade wind intensity and decreased southwesterly monsoonal flow in the tropical Atlantic during the last glacial maximum [Williams et al., 1974; Gates, 1976; Manabe and Hahn, 1977; Manabe and Broccoli, 1983; Kutzbach and Guetter, 1986; Rind, 1987]. Larger changes in surface winds, increased southeasterly and monsoonal flow, are predicted for 9000 years ago when the Earth's precessional cycle was at a maximum (northern hemisphere summer solstice and perihelion were aligned) and low-latitude seasonal insolation was enhanced [Kutzbach, 1981; Kutzbach and Otto-Bleisner, 1982; Kutzbach and Street-Perrott, 1985; Kutzbach and Guetter, 1986]. Paleoclimatic observations, used to predict indirectly past changes in wind stress, generally agree with the GCMs. Studies of lake levels [Street-Perrott and Roberts, 1983; Street and Grove, 1979; Street-Perrott and Harrison, 1984; Butzer et al., 1972], of past dune distribution of continental Africa [Sarnthein, 1978; Fairbridge, 1964], and of deep-sea records of sapropels from the Mediterranean [Rossignol-Strick, 1983; Rossignol-Strick et al., 1982; Rossignol-Strick, 1985] and *Melosira* and phytoliths from the tropical Atlantic [Pokras and Mix, 1985] indicate past precipitation patterns which indirectly infer changes in monsoonal flow. Deep-sea records of aeolian materials [Sarnthein et al., 1981; Kolla et al., 1979; Parkin and Shackleton, 1973; Diester-Haass, 1976] and faunal studies from the tropical Atlantic and Indian oceans [Prell, 1984a,b; Mix et al., 1986; McIntyre et al., 1989] have been used to indicate past changes in wind stress magnitude and direction, although the delivery of aeolian dust to the ocean is dependent on source area aridity as well.

Although these paleoclimatic observations are generally in agreement with the GCM results, the timing and mechanism of wind stress response to insolation changes associated with the precessional cycle (19-23 kyr periodicity) are still unresolved. GCMs predict that surface winds in the tropics instantaneously respond to low-latitude insolation changes independent of the extratropical boundary conditions of the model, and therefore, in the geologic record, low-latitude wind stress changes should be in phase with low latitude insolation changes dominated by precessional cyclicity [Kutzbach and Guetter, 1986]. Observational studies, however, indicate that maxima in monsoonal wind intensity lag behind solstice-perihelion alignment by thousands of years [Street and Grove, 1979; Rossignol-Strick et al., 1982; Rossignol-Strick, 1983; Street-Perrott and Roberts, 1983; Street-Perrott and Harrison, 1984; Rossignol-Strick, 1985; Pokras and Mix, 1985; McIntyre et al., 1989]. The tropical wind system response mechanisms to changes in seasonal insolation and the degree of decoupling between the tropical and extratropical forcing have been discussed in some studies [Prell, 1984a,b; Prell and Kutzbach, 1987]. Our approach is to take advantage of the rapid dynamic response of the surface layer of the tropical Atlantic Ocean to surface winds, and to combine results from an ocean model with observational data to develop a technique to monitor wind stress changes that is independent of continental paleoclimate.

We use a high-resolution ocean model [Philander and Pacanowski, 1984] for the tropical Atlantic to simulate circulation patterns in order to see how changes in wind stress may affect the thermocline structure. The model uses modern seasonal wind stress observations as input [Hellerman and Rosenstein, 1983] and predicts seasonal hydrographic conditions that are in close agreement with observational data [Garzoli and Philander, 1985; Richardson and Philander, 1987]. The model has been discussed and evaluated in detail [Philander and Pacanowski, 1986a,b.; Richardson and Philander, 1987] and demonstrates that wind-induced surface currents play a primary role in the adjustment processes of the upper ocean. The upper ocean is decoupled from the deep ocean, and its seasonal thermal structure is determined by surface winds [Philander and Pacanowski, 1980].

Since the model predicts that the thermocline structure and surface ocean circulation adjusts to wind stress changes, on geologic time scales, instantaneously (a few months) [Philander and Pacanowski, 1984], wind stress changes in the past can be monitored by measuring parameters that indicate changes in the thermocline structure. Because foraminifera grow throughout the photic zone which has steep thermal gradients in the eastern tropics (Fairbanks et al. [1982], Curry et al. [1983], and this paper, Figure 1) species abundances can be used to record vertical hydrographic gradients which respond to wind changes. Since the tropics is a region where last glacial maximum (LGM) continental evidence contradicts estimated sea surface temperatures [Rind and Peteet, 1984], there is further reason to examine the ocean faunal data. While one of the primary purposes of the CLIMAP Project Members [1981] approach of using faunal assemblages to reconstruct sea surface temperature (SST) fields was to generate input for a LGM atmospheric model simulation, the purpose of this study is to generate a reconstruction of the upper water column hydrography to compare with ocean model simulations. Therefore we take advantage of the fact that species abundances in the tropics respond to hydrographic conditions other than SST. The integration of the model provides a way of predicting past changes in the magnitude and direction of tropical wind and a way of assessing to what extent faunal changes in the tropical Atlantic can be explained by wind stress changes predicted by GCMs and paleowind observations.

In this paper, planktonic foraminifera assemblages from core tops are correlated to the hydrography of the ocean surface layer. The seasonal hydrography is characterized by using empirical orthogonal function (EOF) analysis of the annual temperature range versus depth in the ocean surface layer. The EOF mode weightings of a model simulation of the modern tropical Atlantic ocean circulation is compared to the EOF mode weightings of modern observations [Levitus, 1982]. Finally, an experiment where winds are systematically doubled shows which areas are hydrographically most

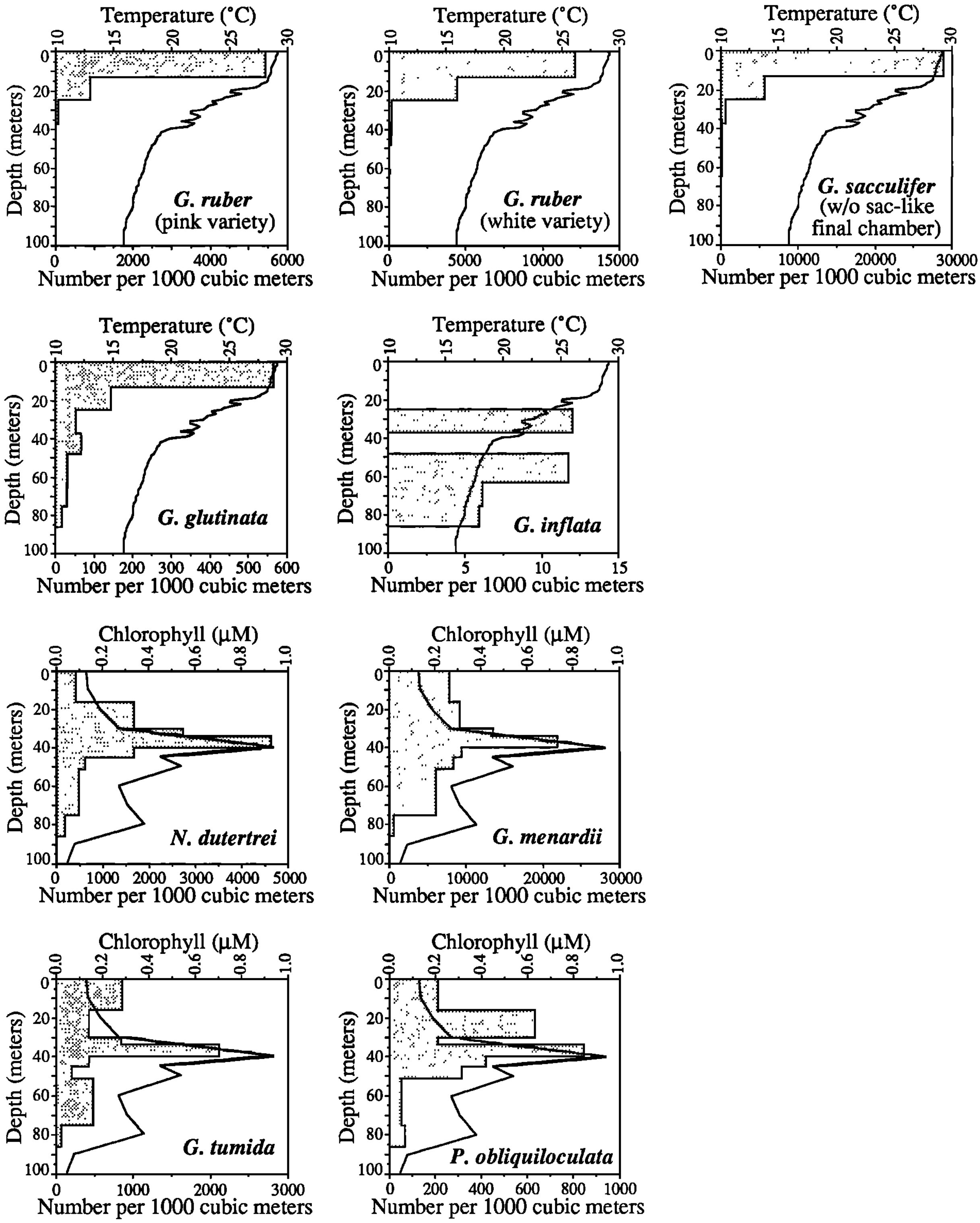

Fig. 1. East equatorial plankton tow abundances for nine species. Histograms of *G. ruber* varieties, *G. sacculifer* (without sac-like final chamber), *G. inflata*, and *G. glutinata* are shown with a temperature profile measured during their collection (2°S, 11°W). Histograms of *N. dutertrei*, *G. menardii*, *G. tumida*, and *P. obliquiloculata* are shown with *a* chlorophyll profile measured at the location of the tows (4°N, 6°W).

sensitive to wind stress increases. Thus far, there have been no ocean model simulations of past times using GCM-generated surface wind fields. This is our next objective. However, LGM faunal data are interpreted in light of the core top correlation with modern hydrography.

TROPICAL ATLANTIC CIRCULATION

Seasonal changes in surface winds of the tropical Atlantic, associated primarily with meridional migrations of the Intertropical Convergence Zone (ITCZ), drive the tropical surface currents. In March and April the ITCZ is close to the equator, winds at the ITCZ are relaxed and surface currents are weak and westward, and the strength of the northeast trades and the North Equatorial Current (NEC) are at a maximum. The thermocline generally slopes from the southeast where it is shallow to the northwest where it is below the photic zone (the top layer of the ocean through which light penetrates). In May the southeast trades intensify and the ITCZ moves northward. At 3°N the westward flowing South Equatorial Current (SEC) intensifies and between 3°N and 10°N, the North Equatorial Current becomes the eastward flowing North Equatorial Countercurrent (NECC). Garzoli and Katz [1983] suggest that the reversal of the trade winds at this time is responsible for the reversal of the NECC. Ship drift measurements show that the reversal occurs in winter and spring in the western Atlantic [Richardson, 1984]. Overall, the NECC flow is warm and most intense in August and October when it depresses the thermocline just north of the equator all the way across the Atlantic Ocean. The magnitude and direction of the tropical Atlantic oceanic currents as well as the upwelling of cold waters and the advection of extratropical waters can all have profound effects on the thermal structure of the water column (the depth of the mixed layer and the gradient of the thermocline) [Merle, 1983].

Regional upwelling brings cool waters and nutrients into the photic zone making the eastern tropics a region with high surface productivity and steep thermal gradients. Upwelling is not limited to the coastal regions; upwelling causes the regional "doming" of the thermocline as well. Generally, the thermocline dips downward from east to west, with depressions in downwelling areas and doming in upwelling areas. In the east the thermocline is shallow and steep, and in the west the mixed layer is deep and the thermocline is below the photic zone. Variations in the strength of the trade winds control the observed spatial and temporal variations in upwelling and downwelling intensity and therefore in the depth of the thermocline and mixed layer.

There have been a number of projects designed to obtain direct observations of surface flow and wind patterns from the tropical Atlantic in the past few years (Sequal/Focal program [Weisberg, 1984; Garzoli and Katz, 1983; Richardson and Walsh, 1986; Hisard et al., 1986; Katz et al., 1986; Garzoli and Clements, 1986; Katz, 1987]). However, the exact relationship between wind stress, surface currents, vertical meridional transport, and the regional thermocline structure cannot be understood from observations alone. Thus the ocean model that we use is useful in understanding these relationships.

METHODS

In order to use abundances of multiple species of planktonic foraminifera as indicators of thermal gradients and seasonality, it is important to have a good understanding of foraminifera depth habitat and seasonality. Much of the basic groundwork for such an understanding has been done. Several authors document the vertical distribution and seasonality of foraminifera species and zooplankton using abundances [Jones, 1967; Fairbanks and Wiebe, 1980; Ortner et al., 1980; Tolderlund and Be, 1971; Be, 1982; Thunell and Reynolds, 1984]. Isotopic measurements of foraminifera from tows and sediment traps indicate calcification depth and seasonality [Fairbanks et al., 1980; Deuser et al., 1981; Williams et al., 1981; Fairbanks et al., 1982; Curry et al., 1983; Deuser and Ross, 1989]. Typically, certain species are found in greatest abundance in the mixed layer, and some are found in the subsurface thermocline where primary productivity is at a maximum. Figure 1 shows species abundances from plankton tows in the eastern tropical Atlantic, confirming vertical distribution patterns first measured in the eastern tropical Pacific [Fairbanks et al., 1982; Curry et al., 1983]. These studies, which demonstrate that in the tropics depth-stratified planktonic foraminifera species can be used to monitor surface layer hydrography, are the basis for the method used in this study and provide insight for the interpretation of the results of the core top factor analysis.

In order to correlate hydrography to the core top foraminifera faunal assemblages, the seasonal hydrography was reduced to three hydrographic "modes" (Figure 2), and the relative abundances of 29 species of planktonic foraminifera from 118 core tops from between 20°N and 20°S were reduced to three factors using factor analysis. 104 core tops are from Prell's [1985] compilation of the CLIMAP calibration data set, and the remaining 14 core top abundances are from a study by Mix [1985]. Scores for three factors were calculated from the core top abundance data. The core top factor loadings were then correlated to hydrographic parameters discussed below.

EOF Analysis of Hydrography

The hydrography of the tropical Atlantic (20°N to 20°S) was characterized using monthly temperature observations [Levitus, 1982]. The first

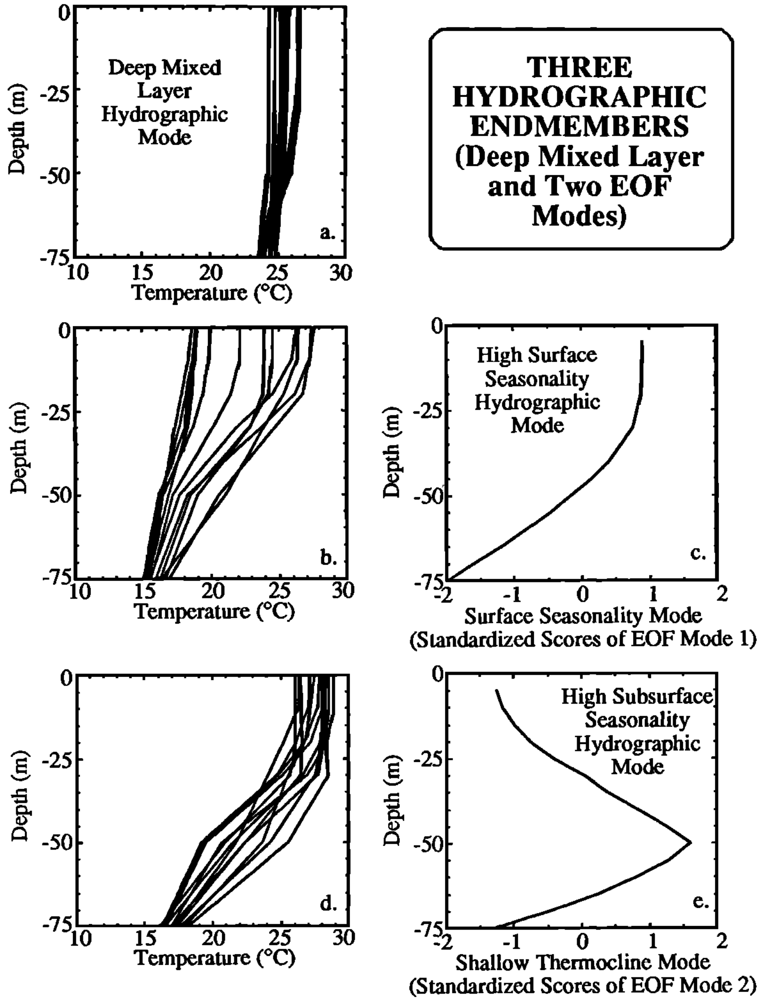

Fig. 2. The three hydrographic end-members. Monthly temperature profiles are shown for (a) the deep mixed layer end-member, (b) the high surface seasonality end-member, and (d) the high subsurface seasonality end-member. The mode scores from the EOF analysis of temperature range as a function of depth are plotted for (c) EOF mode 1 and (e) EOF mode 2.

hydrographic parameter used was annual average mixed layer thickness. Mixed layer depth for each month was calculated by finding the minimum of the second derivative of temperature as a function of depth below sea level. Monthly mixed layer depths were then averaged. The annual average mixed layer depth generally increases westward in the tropical Atlantic (Figure 3). The annual average ocean surface flow from east to west causes warmer surface water to "pile up" in the west and cooler subsurface water to upwell in the east.

The largest seasonal variations in the thermocline depth occur primarily in the western and central tropical Atlantic along and just north of the equator. However, isotopic measurements on foraminifera collected in plankton tows show that the dominant species of planktonic foraminifera in the tropics grow in the photic zone (top 75 m or so) [Fairbanks et al., 1980, 1982], and therefore their fluxes to the seafloor are probably not affected by deeper temperature variations. Therefore we focus only on the top part of the surface ocean layer (upper 75 m), where the largest subsurface temperature variability is in the east in regions where seasonal upwelling brings cool waters into the photic zone. Most of the western tropical Atlantic, despite large seasonal thermocline vertical movements, has a deep mixed layer throughout the year and little seasonality in the photic zone (Figure 2a).

In order to characterize the seasonal variability in the photic zone we reduce the monthly temperature data by doing an empirical orthogonal function analysis (EOF) on annual temperature range as a function of depth. For locations spaced 2° in latitude and 2° in longitude, annual temperature range at 5-m intervals from 0 to 75 m was calculated from cubic

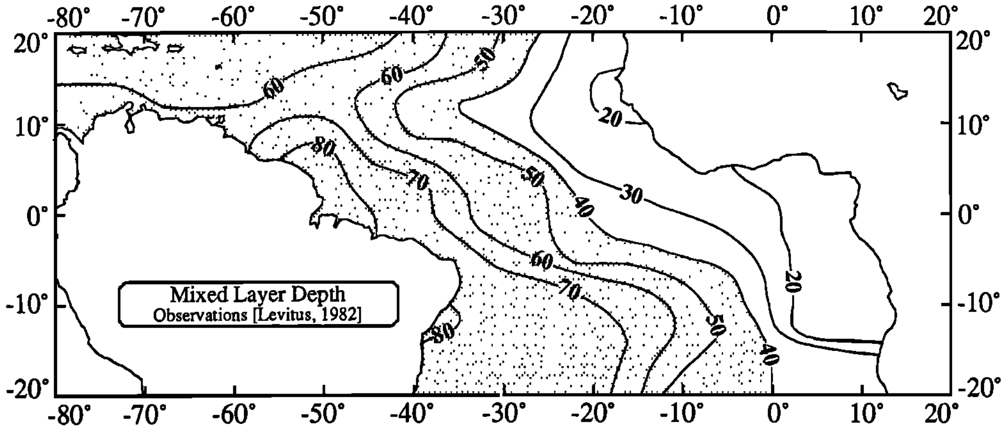

Fig. 3. Observed mixed layer depth (m).

spline interpolated, smoothed monthly average observations compiled by Levitus [1982]. EOF analysis on these temperature range profiles shows that 95% of the variance in temperature range versus depth for the tropical Atlantic can be explained by two modes. Amplitude factors of the modes are calculated in the following way:

$$AF_{ij} = VE_{ij} * \mathrm{sqrt}(VA_j) * \sigma_i$$

where AF_{ij} is the amplitude factor at the ith location for the jth mode, VE is the eigenvector, VA is the eigenvalue, and σ is the standard deviation of the temperature range as a function of depth.

The first mode explains 70% of the variance. Positive amplitude factors of mode one represent high surface seasonality (down to approximately 30 m) and low seasonality at approximately 60-75 m (Figures 2b and 2c). For areas with positive amplitude factors, mode one is called the "surface seasonality" hydrographic mode. The map pattern of the "surface seasonality" mode shows high-amplitude factors concentrated at the margins of the eastern tropical Atlantic in the north and the south (Figure 4). The negative amplitude factors represent areas with low surface seasonality and high seasonality between 60 and 75 m. These areas do not correlate with any of the faunal factors probably because variability at these depths has little influence on foraminifera ecology. Although the negative amplitude factors are not mapped, they are briefly discussed in the following section.

The positive amplitude factors of the second EOF mode represent subsurface seasonality centered at about 50 m (Figure 2d and 2e). This mode has positive amplitude factors in the eastern tropics particularly between 10°N and 3°S (Figure 5). Mode two is referred to as the "shallow thermocline" hydrographic mode since it represents an end-member with high subsurface seasonality due to large annual variations in the depth of the shallow thermocline centered at approximately 50 m. Negative amplitude factors of EOF mode two represent areas where there is relatively low seasonality at 50 m and do not consistently correlate with any of the faunal factors.

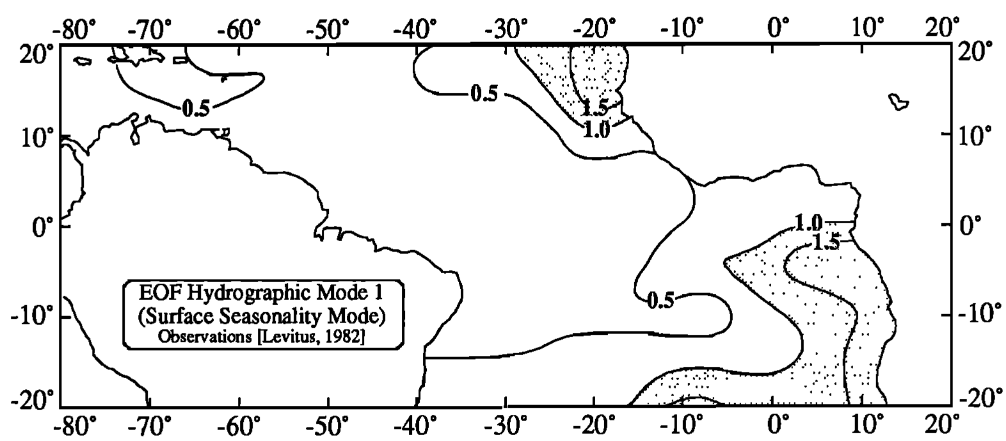

Fig. 4. Distribution of the surface seasonality hydrographic mode (EOF mode 1).

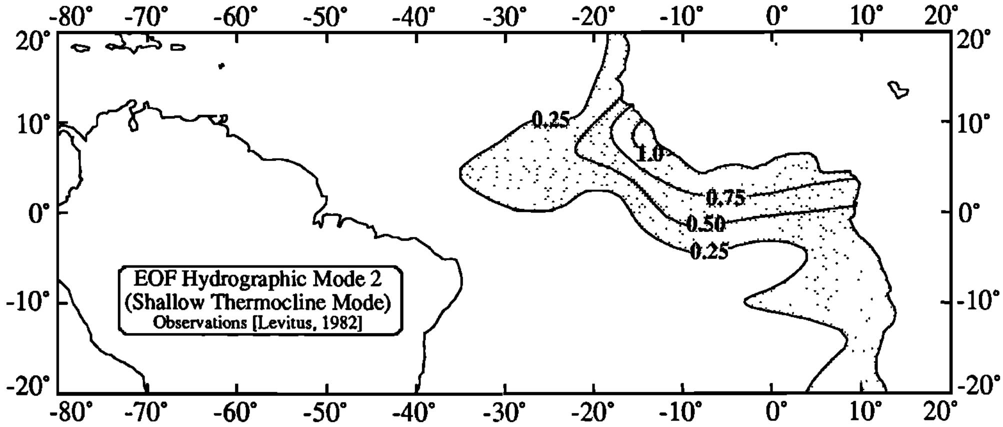

Fig. 5. Distribution of the shallow thermocline hydrographic mode (EOF mode 2).

Factor Analysis of Foraminifera

The planktonic foraminifera relative abundance data were reduced using Q - mode factor analysis with varimax rotation. 89% of the variance of the abundance data can be explained by three factors. The fourth highest eigenvalue indicates that a fourth factor would increase the total variance explained by only 3%. Species scores for the three factors are listed in Table 1.

Species scores for factor 1 are highest for *Globigerinoides ruber* (white variety),

TABLE 1. Varimax Factor Scores (Core tops)

Species	Mixed Layer Factor	Thermocline Factor	Seasonal Succession Factor
Orbulina universa	0.011	0.060	0.038
Globigerinoides conglobatus	0.016	0.033	-0.025
G. ruber (pink)	0.139	-0.028	0.256
G. ruber (white)	0.906	-0.056	-0.036
G. tenellus	0.019	-0.016	0.038
G. sacculifer (without saclike final chamber)	0.278	0.232	0.094
G. sacculifer (with saclike final chamber)	0.129	0.216	0.031
Sphaeroidinella dehiscens	-0.008	0.066	-0.019
Globigerinella aequilateralis	0.092	0.040	0.015
Globigerina calida	0.022	0.001	0.033
G. bulloides	-0.021	-0.034	0.297
G. falconensis	0.021	-0.020	0.105
G. digitata	-0.002	0.035	0.011
G. rubescens	0.035	-0.021	0.021
G. quinqueloba	-0.001	-0.001	0.009
Neogloboquadrina pachyderma (left-coiling)	-0.002	0.003	0.010
N. pachyderma (right-coiling)	-0.015	-0.005	0.179
N. dutertrei	-0.052	0.612	0.136
Pulleniatina obliquiloculata	-0.000	0.352	-0.110
Globorotalia inflata	-0.075	-0.005	0.759
G. truncatulinoides (left-coiling)	0.002	-0.001	0.010
G. truncatulinoides (right-coiling)	0.018	-0.001	0.024
G. crassaformis	-0.002	0.075	0.039
"P-D intergrade"	-0.019	-0.007	0.324
G. hirsuta	0.000	0.001	-0.000
G. scitula	0.007	-0.003	0.030
G. menardii	0.047	0.359	0.139
G. tumida	-0.045	0.498	-0.198
Globigerinita glutinata	0.200	-0.021	0.115

Globigerinoides sacculifer (without a sac-like final chamber), and *Globigerinita glutinata* (Table 1). These species are found in greatest abundance in the mixed layer throughout the tropical Atlantic (Figure 1). Factor one is, therefore, called the "mixed layer" factor. The mixed layer factor explains 73.3% of the variance of the abundance data. Relatively high weightings (>0.75) of the mixed layer factor dominate the tropical Atlantic where the mixed layer is greater than about 40 m (Figures 3 and 6).

Species scores for factor 2 (which explains 11% of the variance) are highest for *Neogloboquadrina dutertrei, Pulleniatina obliquiloculata, Globorotalia menardii*, and *Globorotalia tumida*. Plankton tow studies in the tropical Atlantic (Figure 1) indicate that these species are concentrated in greatest abundance in narrow depth ranges in the subsurface thermocline where the chlorophyll concentration and primary productivity are at a maximum [Fairbanks and Wiebe, 1980; Fairbanks et al., 1980; Ortner et al., 1980; Fairbanks et al., 1982]. Since the species with the highest factor scores for factor 2 are found in greatest abundance in the thermocline, factor two is referred to as the "thermocline" factor. The thermocline factor has highest loadings in the eastern tropical Atlantic between the equator and 10°N (Figure 7) where hydrography is best characterized by EOF mode 2 (Figure 5).

Factor 3, which explains 5% of the abundance data is dominated by *G. ruber* (pink variety), *Globigerina bulloides, Globorotalia inflata*, and P/D intergrade. Outside the tropics, *G. inflata*, the species with the highest score, is thought to grow in greatest abundance in surface waters between 13° and 19°C [Tolderland and Be, 1971] and close to the surface in the cold season [Deuser et al., 1981; Deuser and Ross, 1989]. The pink variety of *G. ruber* is thought to proliferate in the warm season [Tolderland

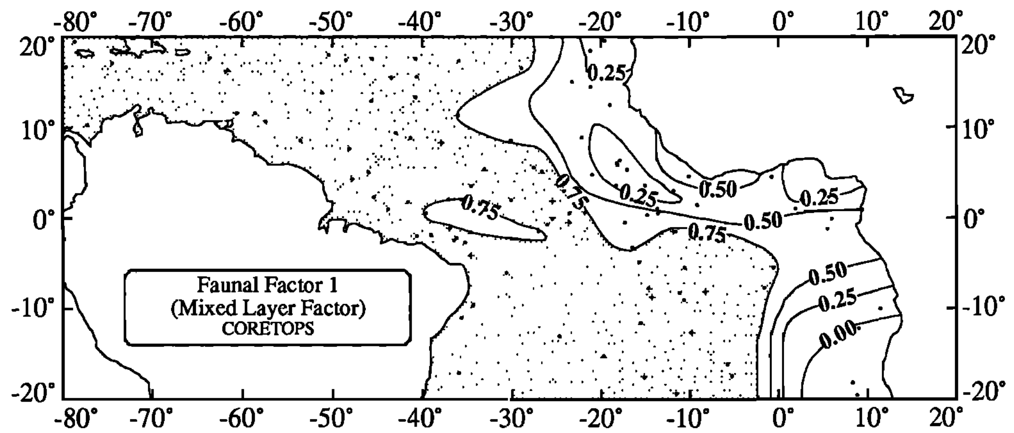

Fig. 6. Mixed layer factor loadings distribution with core top locations. The mixed layer factor is an indication of mixed layer depth.

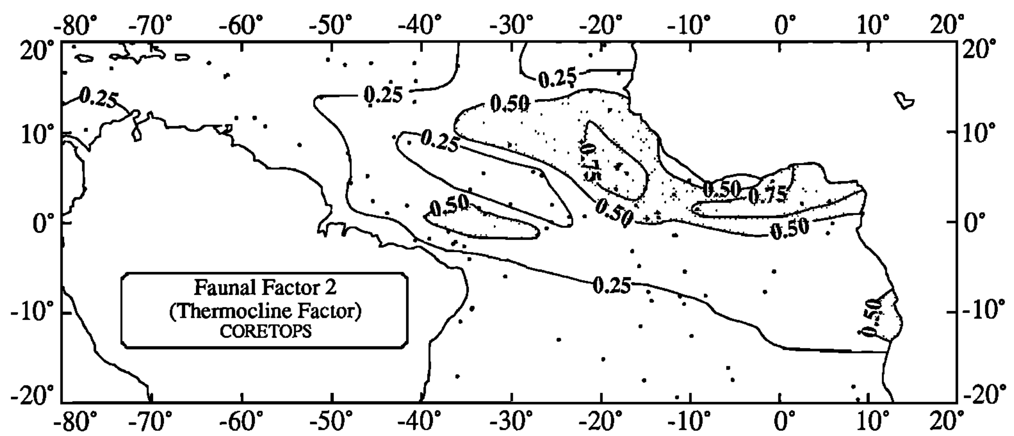

Fig. 7. Thermocline factor loadings distribution with core top locations. The thermocline factor is an indication of thermocline depth. When thermocline factor loadings are high, the thermocline is in the photic zone all year and there is high subsurface temperature seasonality in the photic zone.

and Be, 1971; Williams et al., 1981; Deuser and Ross, 1989]. Since factor 3 is dominated by a combination of cold season species and *G. ruber*, a warm season species, it is called the "seasonal succession" factor. The seasonal succession factor (Figure 8) has highest weightings in the northern and southern margins of the eastern tropical Atlantic. The abundance of *G. inflata* alone may not always be an indication of the sea surface temperature during the cold season, since in some areas of the tropics where surface temperatures are relatively warm, they may grow in the subsurface. In 21 MOCNESS tows from the East Equatorial Atlantic, *G. inflata* is recovered only from the subsurface thermocline. An example is shown in Figure 1.

CORRELATION AND CALIBRATION

Unlike other regions at higher latitudes, the faunal factors in the tropical Atlantic are not strongly correlated to sea surface temperature. Neither the thermocline factor nor the mixed layer factor are correlated with annual average, seasonal minimum, or seasonal maximum sea surface temperature in the tropics (Figure 9a and 9b). The seasonal succession faunal factor does, however, have a fairly good correlation with seasonal minimum sea surface temperature (linear regression $r^2 = 0.616$) but not seasonal maximum sea surface temperature (Figure 9c). This result is encouraging, and it is possible that sea surface temperature estimates as well as the surface layer hydrography can be derived from faunal abundances in the past. Because the circulation and vertical thermal gradients in the tropical Atlantic are quite different relative to the higher latitudes, a new equation for sea surface temperature estimates should be derived for the tropical Atlantic with consideration of the unique hydrography of the tropics. The fact that sea surface temperature estimates in the tropics must be approached with caution is illustrated by the fact that the seasonal succession faunal factor also has a good linear correlation with temperature at 50 m ($r^2 = 0.570$).

There is good first order correlation between the mixed layer faunal factor and mixed layer depth, between the thermocline faunal factor and the shallow thermocline hydrographic mode, and between the seasonal succession faunal factor and the surface seasonality hydrographic mode. The correlations can be seen in the map patterns of the faunal factors and the hydrographic modes. There are a few locations where the correlation between a factor weighting and a hydrographic variable is not good, but these locations can be identified by the weightings of the other factors.

Correlation Between Mixed Layer Factor and Mixed Layer Depth

There is an exponential relationship between mixed layer depth and the mixed layer faunal factor (Figure 10a). High weightings of the mixed layer factor are found in areas with a deep mixed layer, and low weightings are found in areas with a thin mixed layer. Of the core tops with factor weightings greater than 0.8, 95% are located in areas where the mixed layer is 35 m or deeper. For those core tops with factor weightings less than 0.8, 90% are located in areas where the mixed layer is less than 35 m. The few areas that have mixed layer depths more than about 40 m and mixed layer factor weights less than 0.8 have high seasonality in the deep part of the analyzed water layer between 60 and 75 m. These areas can be identified in the sediment by also having low weightings of the seasonal succession factor (indicating low surface seasonality), and moderate weightings of the thermocline factor (indicating thermocline seasonality below 50 m).

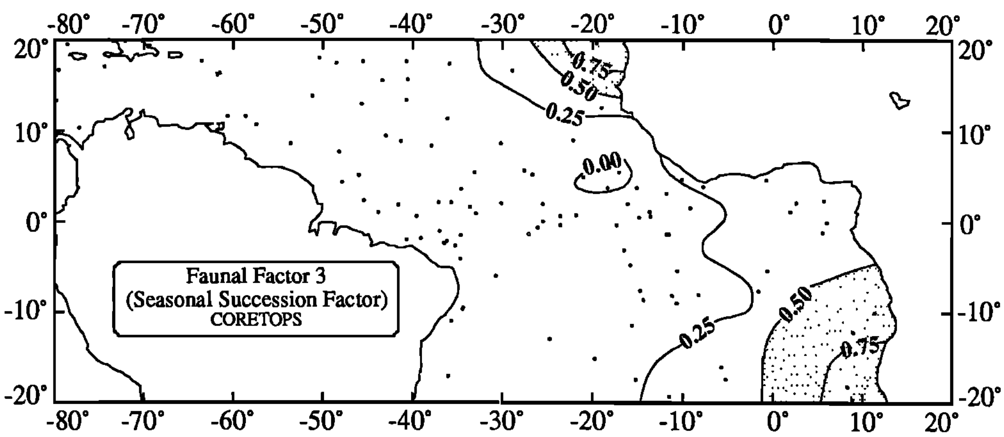

Fig. 8. Seasonal succession factor loadings distribution with core top locations. The seasonal succession factor is an indication of surface temperature seasonality.

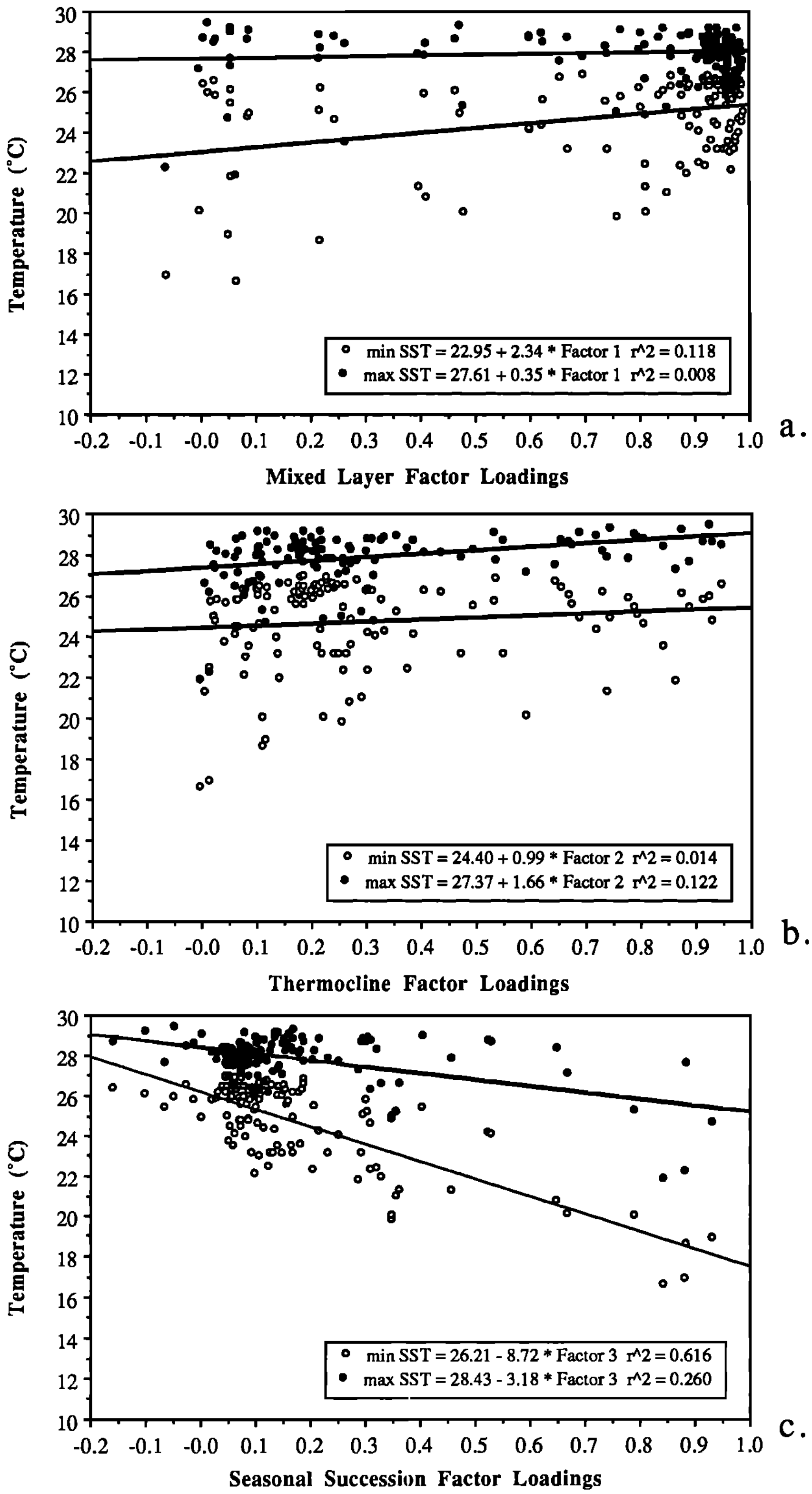

Fig. 9. Factor loadings plotted against annual minimum and maximum sea surface temperature for (a) the mixed layer factor, (b) the thermocline factor, and (c) the seasonal succession factor. There is good correlation only between the seasonal succession factor and minimum sea surface temperature.

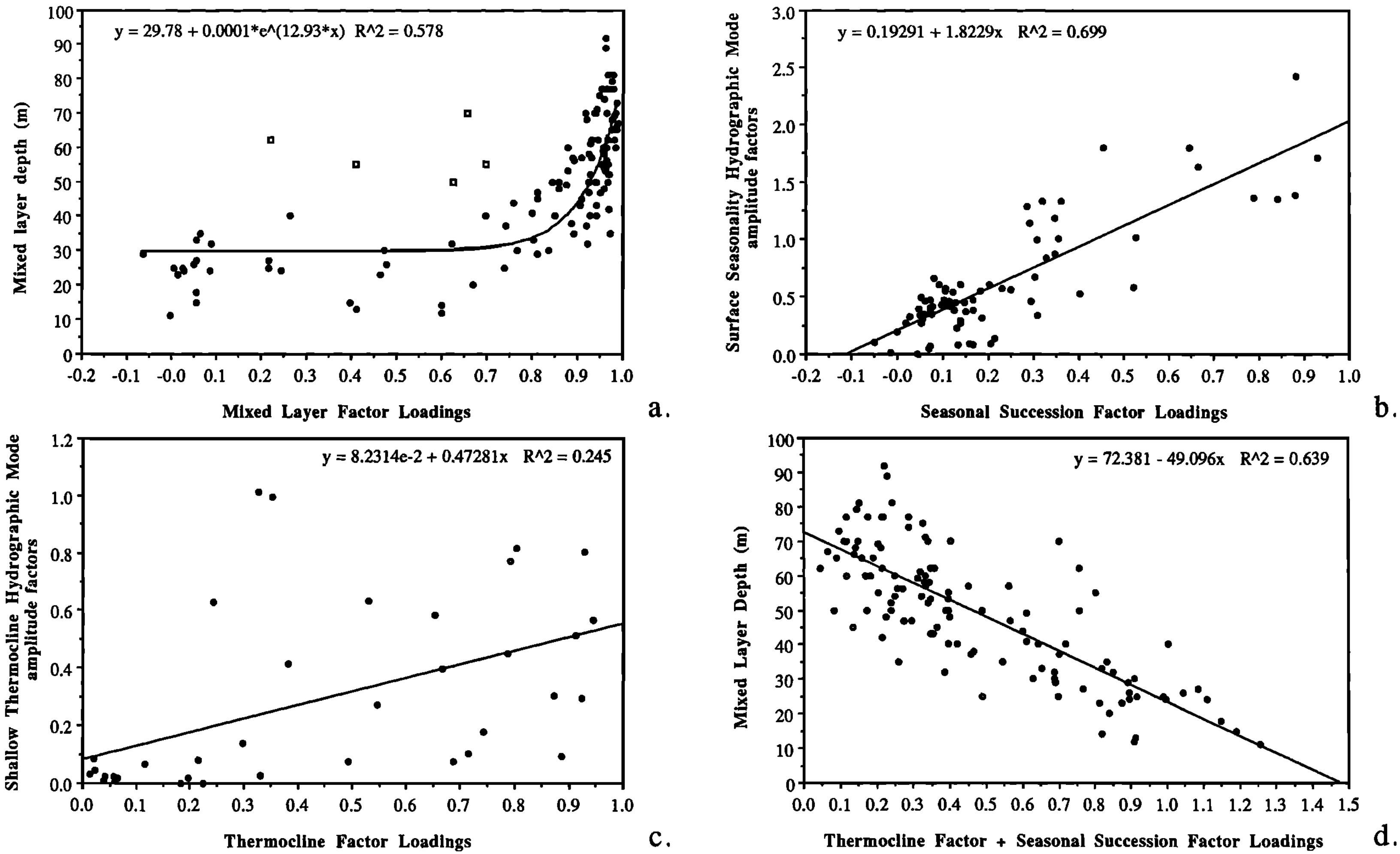

Fig. 10. Scatter plots of factor loading correlations with the hydrographic end-members. (a) Mixed layer faunal factor has a exponential relationship with mixed layer depth. The open squares are those core top samples with mixed layer factor weightings and thermocline factor weightings between 0.1 and 0.8 and very low seasonal succession factor weightings (less than 0.1). These core top samples represent an area where the thermocline movements are centered deeper than 50 m. (b) The seasonal succession factor has a linear relationship with the surface seasonality hydrographic EOF mode. (c) The thermocline factor indicates whether there is shallow subsurface variability represented by the shallow thermocline hydrographic EOF mode. (d) The thermocline factor and the seasonal succession factor together are a good indication of mixed layer depth.

Correlation Between the Seasonal Succession Factor and EOF Mode 1

The seasonal succession faunal factor (positive EOF mode 1) correlates linearly with the surface seasonality hydrographic mode ($r^2 = 0.699$) (Figure 10b). Typically, in areas with high amplitude factors of the surface seasonality hydrographic mode (Figure 2b) the thermocline is in the photic zone for at least part of the year. Combined with the thermocline factor weightings, the seasonal succession factor can also be used to predict mixed layer depth (Figure 10d).

The negative amplitude factors of EOF mode 1 represent a very different type of hydrography with maximum seasonality at 75 m. All locations with overlying hydrography represented by negative EOF mode 1 has seasonal succession faunal factor weightings below 0.2. It is not surprising that the seasonal succession factor, which records surface temperature variation, does not covary with seasonality at depth represented by the negative amplitude factors.

There is also a fairly good correlation between the seasonal succession faunal factor and seasonal minimum sea surface temperature (Figure 9c). However, the fact that *G. ruber* has significant score weightings in the seasonal succession faunal factor indicates that this factor is more closely related to seasonality than to minimum sea surface temperature in the modern tropical Atlantic. In addition, it is important to consider in paleo-reconstructions that *G. inflata* grows below the surface in some regions of the tropical Atlantic (Figure 1).

Correlation Between the Thermocline Factor and EOF Mode 2

The thermocline faunal factor is a good indication of thermocline depth and subsurface seasonality. When the largest seasonal variations in temperature are centered at 50 m below the surface in the water column (positive EOF mode 2), then the thermocline factor weakly correlates with the shallow thermocline hydrographic mode (Figure 10b). This correlation is not strong for several reasons. As discussed above, moderate values of the thermocline faunal factor can also occur where there is high subsurface seasonality due to movements of the thermocline in the deeper part of the water column (60-75 m). In this case, the thermocline faunal factor will not correlate well with EOF mode 2 which indicates seasonality shallower than 75 m. In some cases, the location of the thermocline through most of the year, and the depth of maximum subsurface seasonality is very shallow (approximately 30 m). In these locations the thermocline faunal factor will not correlate with EOF mode 2 which indicates seasonality centered at 50 m, not 30 m.

Since the thermocline factor and the shallow thermocline hydrographic mode do not correlate well, it is more useful to think of the thermocline factor as filling in when the surface temperature seasonality is not large and when the mixed layer depth is small (less than about 40 m). When the thermocline factor dominates or when it has moderate weightings with the seasonal succession factor, the overlying thermocline is in the photic zone and the mixed layer is shallow (Figure 10d).

Negative amplitude factors of EOF mode 2 are found in regions that have either positive amplitude factors of EOF mode 1 or have deep mixed layer depths. Therefore the hydrography in these areas are represented by the seasonal succession or the mixed layer factor.

Testing the Correlations

In order to test the correlations described above, they are recalculated using 1/3 of the core top data set, and the calibration to the hydrographic parameters is tested on the remaining 2/3 of the data set. For the calibration between mixed layer factor and mixed layer depth, the residuals (predicted mixed layer depth minus observed mixed layer depth) have a standard deviation of 10.7 m. The residuals produced by using the thermocline plus the seasonal succession factors to calculate mixed layer depth has a standard deviation of 10.9 m. Residuals from the prediction of surface seasonality hydrographic mode have a standard deviation of 0.28, and residuals from the prediction of the shallow thermocline hydrographic mode have a standard deviation of 0.39. The standard deviation of the residuals give an indication of the minimum change in hydrography needed to significantly alter the faunal abundances. These calculations of the residuals of standard deviation are maximum values since in all cases the calibration with 1/3 of the data set explains less of the variance of the hydrographic parameters than the calibration using the entire core top data set.

OCEAN MODEL

The ocean model from the Geophysical Fluid Dynamics Lab [Philander and Pacanowski, 1986a,b] covers an area from 28°S to 50°N, has 27 levels in the vertical down to 4149 m with 10 levels in the top 100 m of the water column. The longitudinal resolution is 1°, or 100 km near the equator. The north-south grid spacing increases from about 33 km near the equator to about 200 km at 20°N and 20°S. The model output has been compared to observations in past studies [Garzoli and Philander, 1985; Richardson and Philander, 1987]. Below, the photic zone temperature output from the standard model run is compared to observations compiled by Levitus [1982] in terms of the three hydrographic parameters discussed earlier (mixed layer depth, the high seasonality EOF mode, and the shallow thermocline EOF mode). Changes in the map patterns of these parameters due to doubling the wind stress show which areas are most likely to show faunal assemblage changes due to increasing wind strength.

For the standard wind stress run used in this study, the initial conditions are zero currents and climatological temperature and salinity fields of January [Levitus, 1982]. The model was forced by the observed wind field compiled by Hellerman and Rosenstein [1983]. A 40-min time step was used, with seasonal equilibrium reached in 2 years. The standard model run output described below is from the third year.

Standard Wind Stress Run

Mixed layer depth and amplitude factors of the EOF modes were calculated from the standard model temperature output. Projection of the EOF modes on the model output explains 80% of the model temperature variance. The model predicts mixed layer depths of 30 m and less in the eastern part of the tropical Atlantic (Figure 11) that is in close agreement with the observations (Figure 3). In the west the model simulates mixed layer depths which are approximately 10-20 m too shallow. This is a result of problems with the parameterization of mixing processes discussed by Richardson and Philander [1987]. Despite these discrepancies the model simulation provides a fairly accurate prediction of deep mixed layer hydrography Modeled minus observed residuals of mixed layer depth have a standard deviation of 10.4 m.

The map pattern of the surface seasonality hydrographic mode for the standard model run (Figure 12) is similar to that of the observations (Figure 4) with the northeastern and southeastern margins of the study area having the highest values. In the northeast region of high amplitude factors (15°N, 20°W), the model underestimates the surface seasonal temperature range with the seasonal minimum temperature about 2°C warmer than the observations. In a region in the southeast (centered at about 10°S, 10°W), the model overestimates the surface seasonality hydrographic mode because the

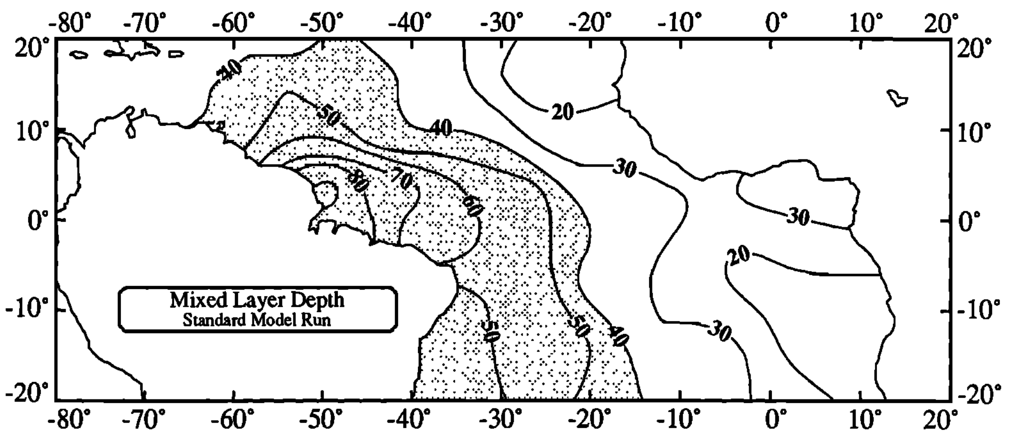

Fig. 11. Mixed layer depth (m) predicted by the standard model run.

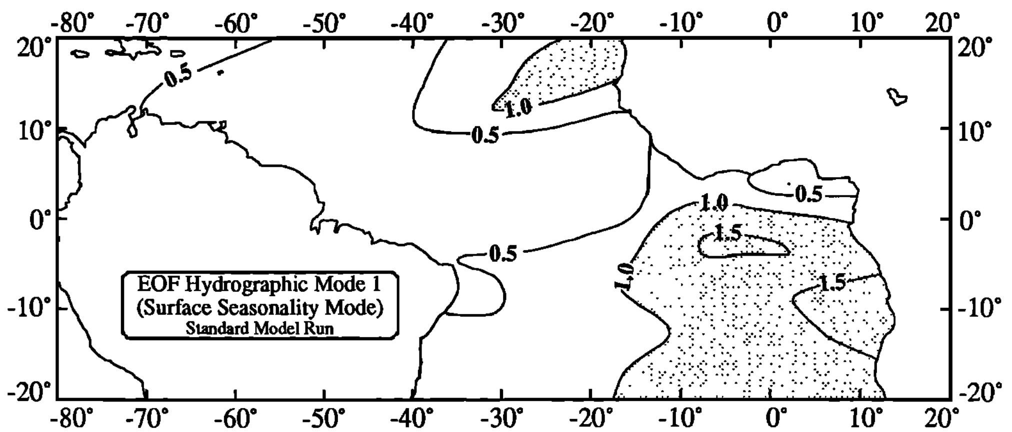

Fig. 12. Distribution of surface seasonality hydrographic mode (EOF mode 1) predicted by the standard model run.

difference between the temperature range at the surface and at 75 m is greater than what is observed. The residuals, modeled minus observed values of the surface seasonality hydrographic mode, have a standard deviation of 0.43.

In the model, the highest amplitude factors of the shallow thermocline hydrographic mode occurs along and just north of the equator in the eastern region of the tropical Atlantic (Figure 13). This map pattern is generally in agreement with the observations (Figure 5) with the exception of the very high amplitude factors in the Gulf of Guinea in the model simulation. This discrepancy can be explained by an underestimation of the observed subsurface temperature range at about 50 m due to averaging. Observed instantaneous temperature profiles from this region [Mele and Katz, 1985] from September and March (Figure 14) indicate that the rate of temperature change with depth at any one time is higher than the monthly average because the thermocline is not located exactly at the same depth during the same month from one year to the next. Therefore computing monthly averages effectively decreases the steepness of the thermocline and the subsurface temperature range. In this case, the model provides a more accurate estimate of subsurface temperature gradients than does the averaged observations. Any other discrepancies between the model (Figure 13) and the observations (Figure 5) are comparable to the standard deviation of the residuals produced by the faunal predicted amplitude factors.

Doubled Wind Stress Run

The double wind stress run was forced by winds with the same direction and doubled magnitude relative to the standard run. The purpose of the double wind stress run was to identify the regions most sensitive to increases in wind stress changes. The double wind stress experiment is not a realistic simulation of the last glacial maximum or of the deglaciation and does not give us insight into changes in seasonality of the winds.

The difference between mixed layer depth predicted by the double wind stress run and the standard wind stress run is contoured in Figure 15. The prominent increase in mixed layer depth all along the equator, particularly close to the continents in both the east and the west, is caused by increased flow in the late northern hemisphere summer of the NECC. With doubled wind magnitude in the summer, the SEC is stronger. The return flow of warm water in the late summer and early fall when the southeasterly trades begin to relax is enhanced, and the thermocline is depressed all the way across the equatorial region from west to east. The increased strength of the SEC causes the shoaling of the thermocline and the decrease in mixed layer depth in the southeast. North of about 8°N doubling the wind stress causes the mixed layer depth to decrease by about 10 m. In this region the standard model run simulates mixed layer depths that are less than observations. Therefore it is possible that in addition to problems with the parameterization of mixing processes, the standard model wind field [Hellerman and Rosenstein, 1983] is stronger than reality [Richardson and Philander, 1987]. The changes in the mixed layer depth due to doubling the wind input would be large enough to dramatically affect faunal abundances, particularly in the eastern half of the tropical Atlantic where the mixed layer faunal factor can be used to predict modern mixed layer depth to within about 10 m.

Doubled wind stress has little affect on the distribution of amplitude factors of the surface seasonality hydrographic mode with the exception of the region close to the equator and the African coast between 15°W and 10°E (Figure 16). This region shows extremely large changes relative to the range of amplitude factors calculated for the standard wind stress run. The decrease in amplitude factors results from a deepening of the thermocline particularly in

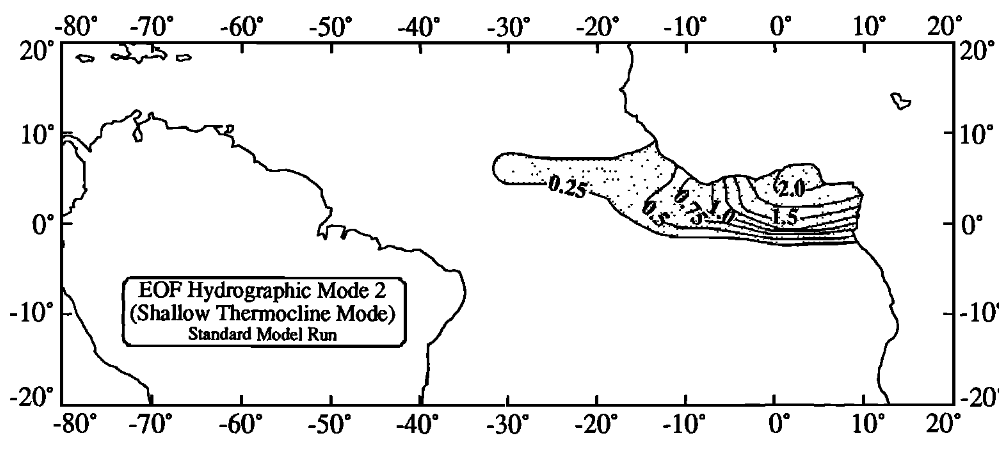

Fig. 13. Distribution of shallow thermocline hydrographic mode (EOF mode 2) predicted by the standard model run.

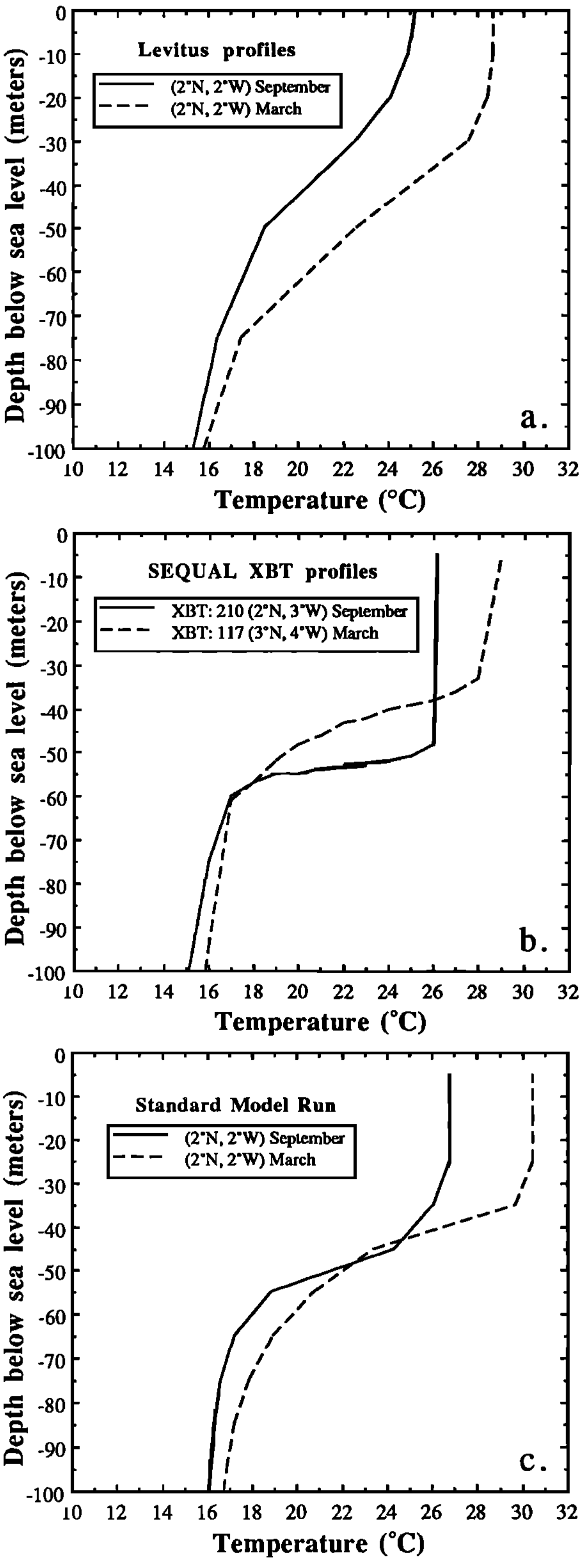

Fig. 14. Temperature profiles of September and March from (a) Levitus [1982], (b) Sequal project [Mele and Katz, 1985], and (c) the standard model run.

the northern hemisphere summer and early fall and the consequent increase in seasonality at depth (60-75 m) relative to the seasonality at the surface.

The region of largest change, due to doubling the wind stress input, for the surface seasonality mode is also the region of largest change for the shallow thermocline mode (Figure 17). The amplitude factors for the shallow thermocline mode decrease when the winds are strengthened because annual thermocline depth variability is centered below 50 m. As can be seen in the difference map for mixed layer depth (Figure 15), the annual mixed layer is as much as 20 m deeper in this region. Amplitude factors of the shallow thermocline hydrographic mode increases with doubled wind stress in the region between 0° and 10°S in the east central part of the tropical Atlantic because the thermocline in on average shallower than it is in the standard model run (centered closer to around 50 m). Mixed layer depth changes (Figure 15) are consistent with a shoaling of the thermocline relative to the standard model run. The changes in the shallow thermocline hydrographic mode due to doubling the wind stress are much greater than what the faunal abundances would respond to and therefore confirm the value of using the faunal factor weightings to monitor changes in the hydrographic modes.

The regions of smallest change due to doubling the wind stress, north of 5°N and south of 5°S in the western half of the study area, are the best places to obtain downcore records of nutrient-depleted stable surface water. Downcore signals from other regions are influenced by regional wind stress changes and should not be used for "global" records of nutrient-free surface water. This result could have profound effects on studies that stack records from the tropics [Matthews and Poore, 1980; Mix and Ruddiman, 1985; Curry and Crowley, 1987; Prentice and Matthews, 1988]. It is possible that a single core from a region that is well chosen for the purposes of a given study would provide a more accurate signal than one produced by stacking records from different regions in the tropics.

APPLICATION TO THE LAST GLACIAL MAXIMUM

The double wind stress run compared to the standard wind stress run indicates that one of the most sensitive areas to wind stress increases is in the eastern to central equatorial region. This region of large change is the best region for downcore monitoring of the wind magnitude increases. Although we have not yet done a model run forced by realistic winds for past times, the double wind stress experiment can be used to make a first guess at whether faunal changes can be explained by wind forced changes in hydrography.

We chose the LGM because it is for this time slice that the most complete spatial sediment sampling is available. First, we must question the validity of

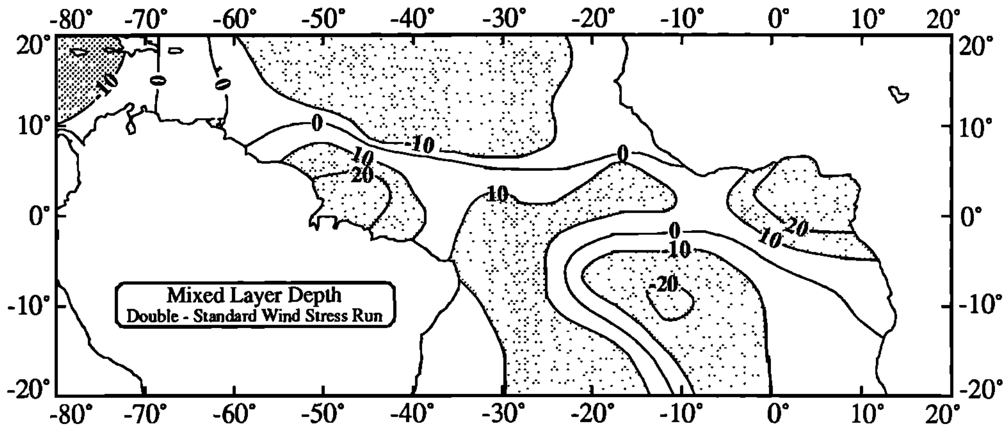

Fig. 15. Difference in mixed layer depth (m) between the double wind stress run and the standard model run. Postive numbers indicate deepening and negative numbers indicate shoaling of mixed layer with double wind stress.

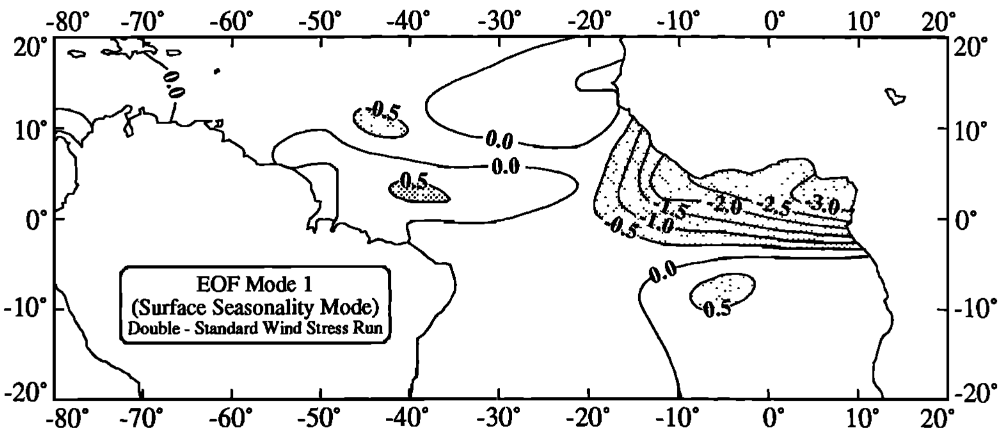

Fig. 16. Difference in the surface seasonality hydrographic mode (EOF mode 1) between the double wind stress run and the standard model run.

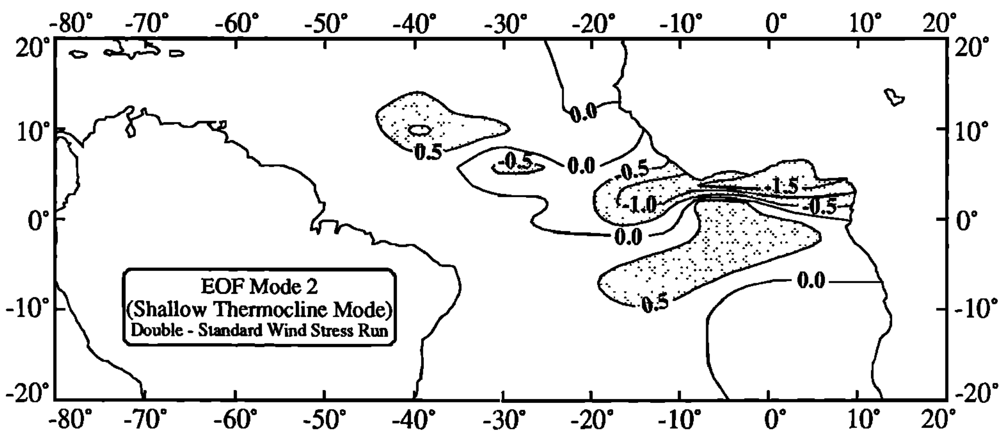

Fig. 17. Difference in the shallow thermocline hydrographic mode (EOF mode 2) between the double wind stress run and the standard model run.

assuming that foraminifera species associations are constant through time. Only about 35% of the variance of the the LGM species abundances can be explained by the core top factors calculated in this study. However, 61% of the variance in the tropical Atlantic LGM level can be explained by the revised CLIMAP Atlantic Ocean FA-20 equations used by Mix [1985]. This may indicate that factors calculated from a larger region than 20°N to 20°S may prove to be more robust. Nevertheless, it is important to consider the unique hydrography of the tropics and the fact that the same species that proliferate in the surface water in the subtropics may proliferate in the subsurface in the tropics. For the purpose of detailed studies of hydrographic changes in the tropics, the faunal assemblages relationships to hydrographic parameters should be examined regionally rather than oceanwide. Although the region of this study from 20°N to 20°S covers most of the tropics, we expect that the variance explained in the LGM level by the core top factors may increase if the study area is increased in size by 5°-10° farther north to make the region more symmetric about the ITCZ rather than the equator.

Regardless of the area from which the factor scores are derived, the LGM faunal assemblages in the tropical Atlantic are not well represented by core top faunal scores. Factor analysis of species abundances from the LGM section of 77 cores in the tropical Atlantic does not produce factors with the same scores as the core top factors (Table 2). In the LGM scores,*G. inflata* is an important species in both the thermocline and seasonal succession factors, several important species in modern sediments are not found, and *G. bulloides* becomes an important species in the seasonal succession factor. Thus factor analysis can be used on the abundance data sets from past time slices to determine if species associations change through time.

Contoured maps of the three faunal factors produced by factor analysis of the LGM abundance data set are shown (Figures 18, 19 and 20). There is a mixed layer factor (explaining 67% of the variance) whose loadings suggest reduced mixed layer depth in the central part of the tropical Atlantic (Figure 18). In the second factor of the LGM analysis, like in the core top thermocline factor, species which live in the thermocline, *N. dutertrei, G. inflata,* and P/D

TABLE 2. Varimax Factor Scores (LGM)

Species	Mixed Layer Factor	Thermocline Factor	Seasonal Succession Factor
Orbulina universa	0.013	0.015	0.054
Globigerinoides conglobatus	0.031	0.019	-0.020
G. ruber (pink)	0.070	0.019	0.242
G. ruber (white)	0.928	0.006	0.097
G. tenellus	0.036	-0.019	0.025
G. sacculifer (without saclike final chamber)	0.169	0.212	-0.021
G. sacculifer (with saclike final chamber)	0.079	0.209	-0.062
Sphaeroidinella dehiscens	0.000	0.000	0.000
Globigerinella aequilateralis	0.101	-0.010	0.021
Globigerina calida	0.009	0.017	0.028
G. bulloides	-0.073	-0.150	0.700
G. falconensis	0.027	-0.011	0.114
G. digitata	0.004	0.010	-0.001
G. rubescens	0.042	0.005	0.015
G. quinqueloba	-0.002	-0.002	0.012
Neogloboquadrina pachyderma (left-coiling)	-0.002	0.004	0.015
N. pachyderma (right-coiling)	-0.050	0.047	0.245
N. dutertrei	-0.037	0.845	-0.124
Pulleniatina obliquiloculata	0.010	0.004	0.001
Globorotalia inflata	-0.069	0.188	0.447
G. truncatulinoides (left-coiling)	0.006	-0.002	0.008
G. truncatulinoides (right-coiling)	0.064	0.103	-0.006
G. crassaformis	-0.001	0.106	0.031
"P-D intergrade"	-0.116	0.335	0.357
G. hirsuta	0.001	-0.001	0.000
G. scitula	0.010	0.004	0.030
G. menardii	-0.004	0.006	0.036
G. tumida	-0.002	0.006	0.009
Globigerinita glutinata	0.230	0.043	0.115

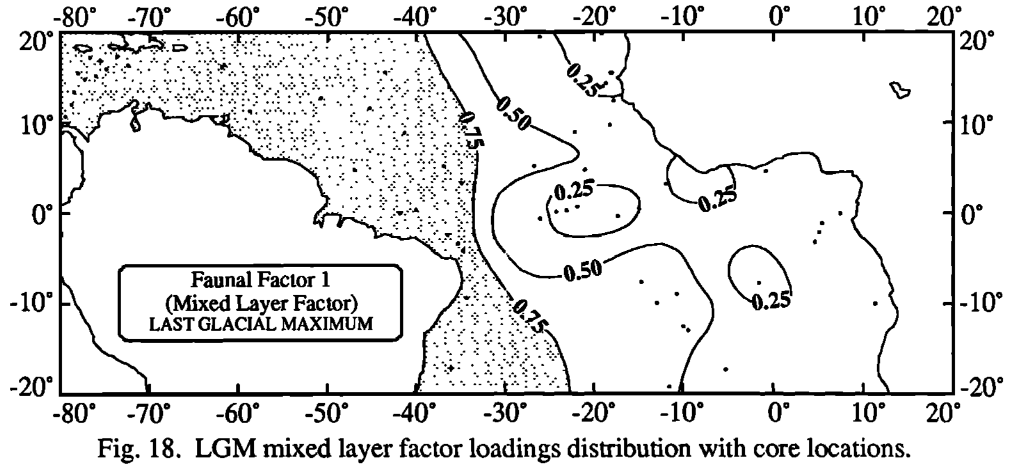

Fig. 18. LGM mixed layer factor loadings distribution with core locations.

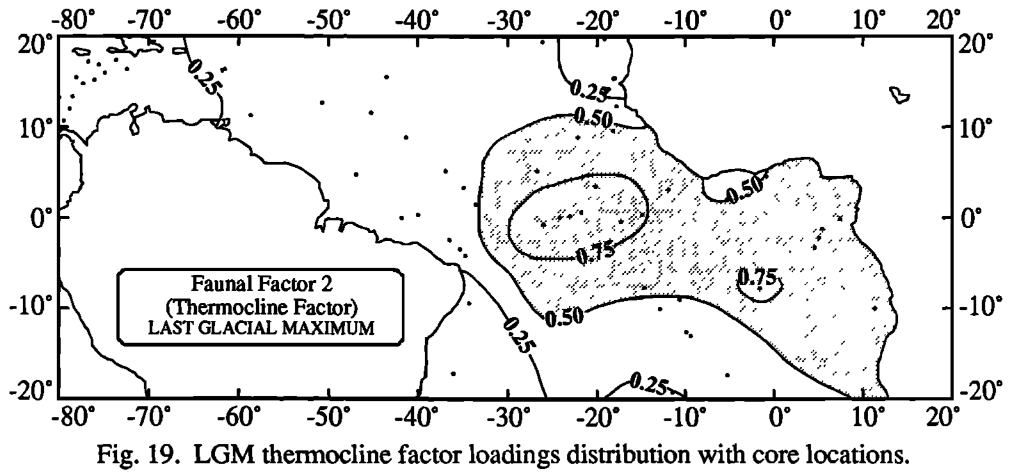

Fig. 19. LGM thermocline factor loadings distribution with core locations.

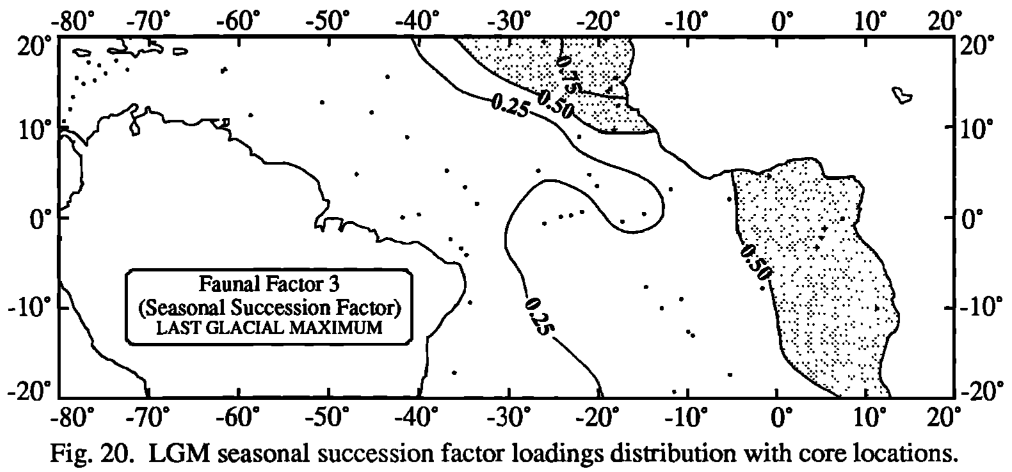

Fig. 20. LGM seasonal succession factor loadings distribution with core locations.

intergrade, and species which live in the mixed layer, *G. sacculifer* (with and without a sac-like final chamber), have high scores. Loadings of the LGM thermocline factor (explaining 14% of the variance) indicate that there was a permanent thermocline in the photic zone and subsurface seasonality (Figure 19) in an area from 10°N to 10°S in the central and eastern regions and generally in the west. The third factor (explaining 7% of the variance) is similar to the core top seasonal succession factor but also has high weightings of *G. bulloides*, *G. pachyderma* (right-coiling) and P/D intergrade. This factor indicates reduced surface seasonality in the south eastern corner of the study area near the continent but slightly increased surface seasonality in the central region between 5° and 20° S (Figure 20).

DISCUSSION

Correlation of Faunal Factors to Hydrography

There are some very important implications from the results of this study that should be considered when trying to predict past oceanic changes from foraminifera assemblages. Since the faunal assemblages of the present ocean are not well correlated with sea surface temperature in the tropical Atlantic, the usefulness of using changes in faunal assemblages to estimate sea surface temperature in the tropics should be reconsidered. For example, high mixed layer factor weightings (>0.9) and low seasonal succession and thermocline factors (<0.1) can be found in areas that have deep mixed layers with an average sea surface temperature anywhere between 22°C and 27°C (Figure 9). Since sea surface temperature estimates using transfer functions require unreasonable lapse rates to explain continental snow line observations [Rind and Peteet, 1984], there is reason to believe that the estimates are too warm. The inability to resolve past sea surface temperature changes using foraminifera assemblages, particularly for the area of deep mixed layer (western tropics), means that other methods such as oxygen isotopic analyses may be the best way of estimating past sea surface temperatures in this region.

The faunal factor correlations with the parameters of photic zone hydrography are straightforward when foraminiferal ecological habitats are considered. Species with high scores of the mixed layer factor have symbiotic algae and are adapted to relatively nutrient depleted upper levels of the photic zone [Hemleben et al., 1989]. In regions with a well-developed mixed layer that extends below the photic zone, mixed layer species dominate over species of the other two factors which grow in association with the higher nutrient, cooler upwelling waters.

The seasonal succession factor correlates with the surface seasonality hydrographic mode because the important species of this factor proliferate in different seasons. Regions with high surface seasonality are in the east at the peripheries of the study area where there is a cold deep mixed layer in the season of high wind stress (winter) and a well-developed shallow thermocline and thin warmer mixed layer in the summer. Besides having high weightings in the seasonal succession faunal factor, these areas have moderate weightings in the thermocline factor because there are times of the year when cool nutrient rich waters are supplied to the photic zone.

Most species with high scores in the thermocline factor are known to proliferate at the level of the thermocline where primary productivity and microzooplankton are at a maximum [Fairbanks and Wiebe, 1980; Fairbanks et al., 1980; Ortner et al., 1980; Fairbanks et al., 1982]. The thermocline factor has high weightings in regions where the ecological habitat that supports the mixed layer species is reduced by nutrient-rich waters upwelling into the photic zone. *G. sacculifer*, a mixed layer species, has fairly high scores in the thermocline factor because a permanent thin mixed layer is still maintained. The thermocline factor does not correlate well with the "shallow thermocline" hydrographic mode because the hydrographic mode is defined as having the thermocline centered at 50 m. However, the fact that in combination with the seasonal succession factor it does correlate with mixed layer depth means that high weightings of either factor or moderate weightings of both should be used as an indication of a thin mixed layer.

Finally, two things that might improve our ability to predict photic zone hydrography from the faunal factors are a better understanding of how much differential dissolution there is and the use of absolute flux rates. Thus far we have chosen not to focus on the effect of dissolution because there appears to be no correlation between core top depth and the factors, but it is still possible that that dissolution effects create some of the scatter in the regression fits. Absolute flux rates of planktonic foraminifera species to the seafloor would probably provide more information that could be tied to photic zone hydrography. While relative abundances indicate the dominance of a certain ecological habitat, absolute fluxes might indicate the combination of habitats more clearly, thus providing a more detailed reconstruction of hydrography.

Comparison of Model Results and Faunal Factors for the LGM

The double wind stress run is not intended to be a simulation of the LGM since GCMs predict small increases, between about 10% [Kutzbach and Guetter, 1986] and 40% [Rind, 1987], only in the northeast trades for the LGM. The double wind stress run is only used to locate areas that are sensitive to wind stress increases. The comparison of double to standard wind stress model runs predicts that some of the areas of largest change for mixed layer depth are the same as those areas which have decreased mixed layer faunal factor weightings. A comparison of the core top mixed layer factor weightings (Figure 6) with the LGM (Figure 18) indicates that the modern eastern boundary of relatively deep mixed layer (indicated by the 0.75 contour) was shifted westward in the LGM. The model shows that the regions that show the major faunal changes in the LGM relative to today (0-10°W in the south and 30-40°W in the north) are sensitive to wind stress changes. However, the model results also suggest that in terms of mixed layer depth, the equatorial region responds in the opposite sense relative to 5-20°N or 5-20°S. This is not seen in the LGM mixed layer factor weightings. The thermocline and the seasonal succession factors of the LGM show the most change relative to the modern between 20°W and 30°W along the equator and between 0° and 10°E in the southern half of the study area. Although the differences in the double and standard wind stress model runs indicate that these areas are somewhat sensitive to wind stress changes (Figures 16 and 17), they are not the most sensitive.

To summarize, there is moderately good agreement between regions where the model is sensitive to wind stress increases and observations of LGM faunal changes in the western equatorial region, and north and south of the equator in the east. However, there is significant difference between the model and observations east of center along the equator.

Discrepancies between the regions predicted to be the most sensitive to wind stress change and the regions that show the largest changes in the LGM relative to the modern will not be resolved until a realistic LGM wind field is used to drive the ocean model. There are several ways that these discrepancies can be explained. (1) It is possible that the double-standard wind stress model runs do not provide information about where the hydrography is most sensitive to wind stress decreases, seasonal changes in the strength of the trades, or changes in the strength of the monsoons. (2) The LGM faunal changes could be forced by extratropical ocean circulation changes rather than wind stress changes [Mix et al., 1986; McIntyre et al., 1989]. By changing the boundary conditions of the ocean model we may be able to simulate the effect of extratropical changes on the region in future model runs. (3) The LGM faunal changes could be due to dissolution of less resistant species which would effectively increase the thermocline weightings and decrease the mixed layer factor weightings. *N. dutertrei*, a relatively resistant species [Berger, 1971; Be, 1977], has the highest score in the thermocline factor which has high weightings in areas where cores are located off of the Mid-Atlantic Ridge.

CONCLUSIONS

1. The photic zone seasonal hydrography of the tropical Atlantic can be characterized by the average annual mixed layer depth and two hydrographic modes. EOF analysis on annual temperature range variation as a function of depth indicates that the annual temperature range profiles at any one location can be explained by two modes. The surface seasonality hydrographic EOF mode has high surface temperature range, and low temperature range at the bottom of the analyzed water column (75 m). The shallow thermocline hydrographic EOF mode has high subsurface temperature range due to seasonal variations in the depth of the thermocline.

2. Factor analysis reduces 29 species of planktonic foraminifera from 118 core tops in the tropical Atlantic to three factors which explain 89% of the variance of the abundance data. Because of the known depth stratification of tropical species in the tropical Atlantic, the three factors are called the mixed layer factor, the thermocline factor, and the seasonal succession factor.

3. Modern hydrography can be predicted by the foraminifera factor weightings using simple correlations. Mixed layer depth correlates with the mixed layer faunal factor and with the thermocline plus seasonal succession factors. Seasonal succession faunal factor weightings are linearly correlated with the surface seasonality hydrographic mode. Moderate to high thermocline faunal factor weightings indicate seasonal temperature variations in the subsurface due to seasonal vertical movements of the thermocline within the photic zone. These correlations raise the possibility that more variance in faunal abundances downcore may be explained by thermocline and seasonality changes than by sea surface temperatures.

4. The ocean model of the tropical Atlantic is compared to modern hydrography in terms of the three hydrographic parameters. Map patterns of mixed layer depth and amplitude factors of the two EOF modes predicted by the model are very similar to those observed. Some discrepancies can be attributed to the effect of averaging data in order to produce the modern observation temperature fields. Most discrepancies are not significant relative to the standard deviation of the residuals produced by the faunal factor predictions of the hydrographic modes. The results demonstrate that the model is appropriate for paleoceanographic applications.

5. The standard wind stress run output is subtracted from output of a model run in which the wind field used as input is doubled in magnitude. The changes due to doubling the wind stress indicate areas that are most sensitive, and should show substantial faunal changes that can be attributed to past increases in the surface wind field. Areas which show small changes are the best places for downcore records of stable surface waters.

6. Factor analysis of LGM faunal abundances produces three factors that represent the three hydrographic parameters. In general, changes in the LGM factor weightings relative to the core top are in some of the same areas which are sensitive to wind stress increases. The area of largest discrepancy is east of center along the equator. Discrepancies could reflect the fact that atmospheric GCM experiments indicate that uniform changes in north and south trade wind strengths did not occur at the LGM, or could be a result of dissolution effects.

Model runs with realistic wind fields for past times may result in more agreement between model and data in the future.

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