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Reassessment of CLIMAP Methods for Estimating Quaternary Sea-Surface Temperatures: Examination Using Pacific Coretop Data Sets

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ABSTRACT

Quantitative analyses of planktonic foraminifer faunal data have been applied to reconstruct the past conditions of surface oceans and to verify the results of climate modeling. In the present study, planktonic foraminifer faunal SST (sea-surface temperature) estimates were evaluated using a calibration set and a test set of newly compiled coretop data from the low-latitude Pacific. A standard CLIMAP-type transfer function based on the IKM (Imbrie-Kipp Method) was developed in estimating SST. Comparisons between the SST function and the depth of thermocline (DOT) transfer function developed on the basis of the same calibration coretop data indicated that the correlation between the planktonic foraminiferal abundance distribution and DOT is more significant than that with SST. This comparison suggests that the DOT effect is a more important environmental control on faunal distributions and abundances. After evaluating the functions with a test set of coretop data, the residuals of SST estimates (ΔSST = estimated - observed SST) were compared with two surface ocean modes which were derived statistically using a principle component analysis of seasonal SST and DOT data of the low-latitude Pacific, as well as an index of carbonate preservation (CPI). The analyses of residuals clearly indicated that the patterns of estimation bias are correlated significantly with the two ocean modes, with a tendency to yield colder estimates for high SST values, and warmer estimates for low SST values, and with a maximum uncertainty around 3° to 4°C. These results also revealed that the carbonate preservation effect may not produce systematic biases. This reevaluation raises questions about the accuracy of faunal SST estimates that are based on the commonly used quantitative techniques, and implies that the CLIMAP low-latitude Pacific SST pattern should be reexamined. From these analyses we suggest that reconstructing DOT or surface ocean modes from planktonic foraminifer faunal data would be more appropriate in future paleoceanographic studies.

(Key words: Paleoceanography, Planktonic foraminifer, Data base, Pacific Ocean)

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1. INTRODUCTION

Retrieval of interpretable climatic signals from marine sedimentary records is important for understanding the causes of past ocean-climate changes. Among the various paleoceanographic proxy indices, the faunal composition of fossil planktonic foraminifers is widely used for reconstructing past sea-surface temperature (SST), salinity, and other environmental variables. Examples of such reconstructions were made by the CLIMAP (1981) for the Last Glacial Maximum (LGM) for surface ocean climate and by the SPECMAP (Imbrie *et al.*, 1989) for the latest Quaternary climatic time series in the Atlantic Ocean.

Such reconstructions of past ocean variability rely on the statistical relationships between coretop faunal compositions and upper-layer ocean conditions. Two well-known techniques exist for extracting quantitative estimates of surface ocean conditions from faunal composition data: the Imbrie-Kipp Method (IKM) (Imbrie and Kipp, 1971; Klovan and Imbrie, 1971; Imbrie *et al.*, 1973; Kipp, 1976) and the Modern Analog Technique (MAT) (Hutson, 1979; Overpeck *et al.*, 1985; Prell, 1985). The IKM uses factor assemblages of modern faunas and multiple regression analyses to calibrate observed environmental variables such as sea-surface temperature (SST) to derive a set of paleoecological equations (transfer functions) for paleoestimation. The MAT computes a dissimilarity coefficient between past and modern faunal data in order to identify the most similar subset of modern analogues. Environmental estimates for past faunas are then obtained by averaging data from the observed environments of the modern analogues. Empirical comparisons on the efficiency of a number of dissimilarity coefficients (Overpeck *et al.*, 1985; Prell, 1985) suggest that the squared chord distance is the most suitable coefficient for paleoecological studies. The validity of these methods of paleoestimation is based on several assumptions (for IKM: see Imbrie and Kipp, 1971; Sachs *et al.*, 1977; Imbrie and Webb, 1981; for MAT: see Overpeck *et al.*, 1985; Prell, 1985) and has been tested in multibiotic comparisons (Molfino *et al.*, 1982) with statistical confirmation (Molfino, 1993).

The climate pattern reconstructed on the basis of quantitative faunal analyses provides an independent verification for climate models which simulate past climates. LGM climate simulations using the General Circulation Model (Gates, 1976a; b; Manabe and Hahn, 1977) or the newly developed Community Climate Model (Kutzbach and Guetter, 1986) using prescribed CLIMAP SSTs have shown that the ice age SST had a substantial impact on global climate. Alternative models (Manabe and Broccoli, 1985a; b) which used prescribed LGM boundary conditions to predict ice age SST revealed a significant discrepancy between the computed and CLIMAP SST patterns, especially in the low-latitude oceans. This discrepancy, along with the possibility of overestimation of CLIMAP SST based on terrestrial evidence (Webster and Streten, 1978), led Rind and Peteet (1985) to lower the CLIMAP SST by 2°C to balance the radiation budget in their ice age climate simulations. This example illustrates the need for accurate reconstruction of SST to verify the results from climate models from which the relative importance of the various factors which contribute to past climate changes can be evaluated. Although initial assessments (Prell, 1985; Broecker, 1986; Anderson *et al.*, 1989) supported the CLIMAP SST estimates, many recent data/model (Lautenschlager *et al.*, 1992; Hoffert and Covey, 1992) and data/data comparisons (Beck *et al.*, 1992; Stute *et al.*, 1992;

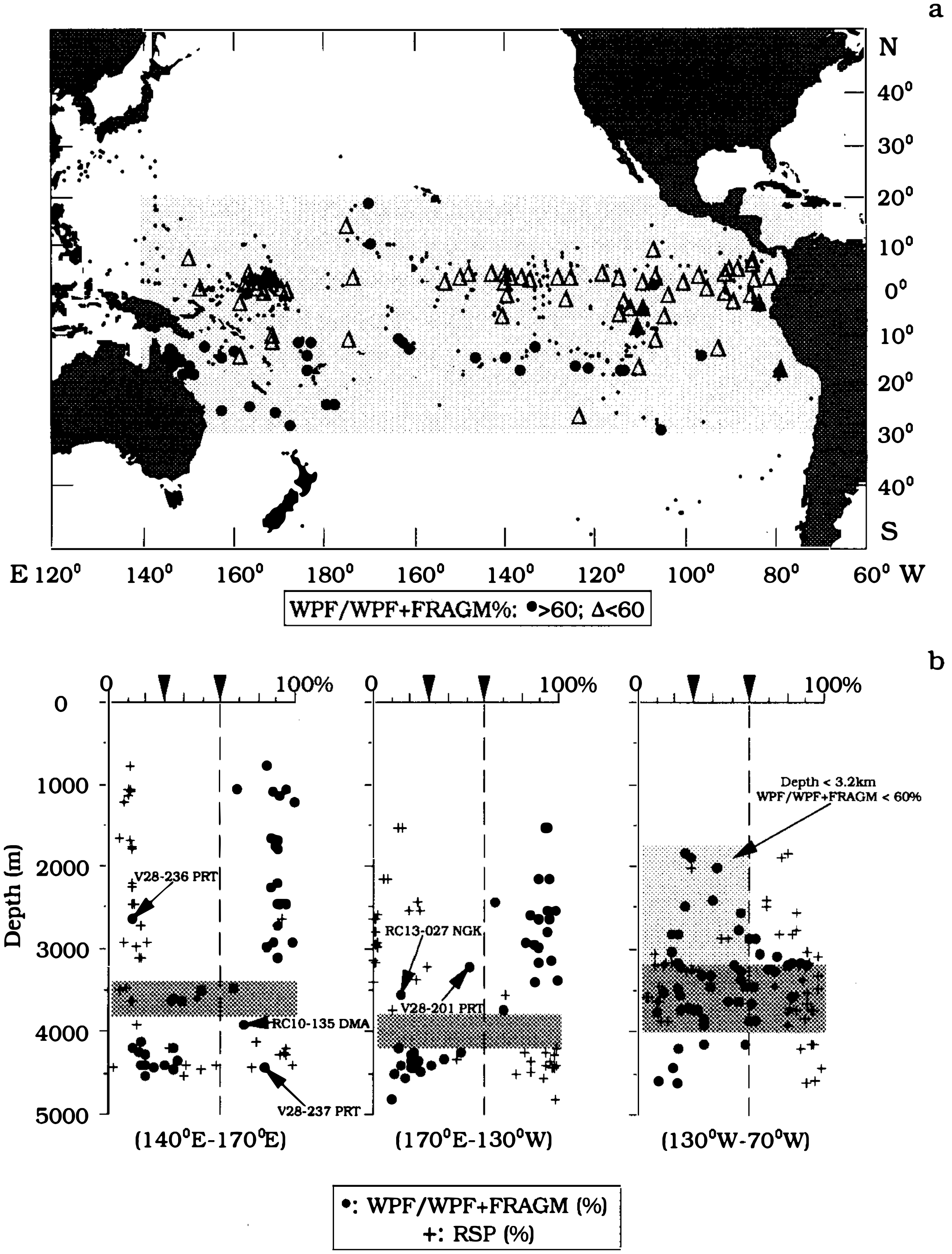
Guilderson *et al.*, 1994) indicate that CLIMAP SSTs, particularly in the low-latitude Pacific, need to be further examined.

Substantial progress has been made by applying the IKM or MAT to estimate Pacific SST using planktonic foraminifers (Luz, 1977; Moore *et al.*, 1980; Thompson, 1976; 1981; Prell, 1985; Le, 1992), but relatively little has been done to evaluate the accuracy of these estimates. In this study, a thorough comparison and evaluation of these models was done with the intention of identifying possible sources of estimation bias. This study sheds new light on the interpretation of biotic indices for ocean processes and will help to develop and improve estimation methods in paleoceanography. The results presented here indicate that the CLIMAP low-latitude Pacific SST pattern may need revision and that a more detailed understanding of the ecology of planktonic foraminifers is needed in order to reduce biases when using paleoestimation techniques.

2. BACKGROUND AND RESEARCH STRATEGY

The planktonic foraminifers in the Pacific surface sediments are not as well preserved as those in other oceans. Previous studies of the Pacific surface sediment faunas (Parker and Berger, 1971; Bé, 1977; Coulbourn *et al*, 1980) revealed the lack of a strong systematic relationship between faunal composition and SST. In viewing the complicated distribution patterns of faunal assemblages, many investigators have suggested that other environmental factors, particularly the differential carbonate preservation of the assemblages, might be responsible for the non-systematic relationship between faunal composition and SST. In principle, the local rain rate of organic carbon and the ΣCO_2 content of the surrounding bottom waters jointly determine preservation conditions and affect the composition of calcareous faunal assemblages. Many field studies have provided evidence for a systematic relationship between preservation state and faunal composition of planktonic foraminifers (Adelseck and Berger, 1975; Adelseck, 1977; Berger, 1968; 1979; Parker and Berger, 1971; Thunell and Honjo, 1981a; b; Malmgren, 1983; Cullen and Prell, 1984; Peterson and Prell, 1985), indicating that the state of carbonate preservation is an important environmental control in the distribution of faunal assemblages.

Planktonic foraminifers grow throughout the photic zone (0 - 80 m) in the upper oceans, and on the thermocline—a layer exhibiting a rapid change in temperature. Because the depth of thermocline (DOT) is an important environmental boundary that partitions faunal assemblages into different depth habitats, the changing position of DOT with respect to the photic zone is considered the primary agent by which the relative abundances of shallow- and deep-dwelling species in the faunal assemblages are modified. Detailed studies of vertical variations in faunal and isotopic compositions of planktonic foraminifer fluxes (Fairbanks and Wiebe, 1980; Fairbanks *et al.*, 1980; Deuser *et al.*, 1981; Fairbanks *et al.*, 1982; Curry *et al.*, 1983; Thunell *et al.*, 1983; Thunell and Reynolds, 1984; Bé *et al.*, 1985; Deuser and Ross, 1989; Ravelo and Fairbanks, 1992) revealed a vertical stratification signal that should be discernible in sedimentary assemblages. The thermocline-controlled pattern of planktonic foraminifers on surface sediments was revealed by studies in the tropical Pacific (Luz, 1973) and the tropical Atlantic (Ravelo *et al.*, 1990), and was considered as one of the most important factors that



could introduce a non-systematic relationship between SST and the "gyre-margin assemblages" (Kipp, 1976) or the "low-latitude assemblages" (Molfino *et al.*, 1982) of the faunas.

As discussed above, observational evidence indicates that the distribution of planktonic foraminifers in modern surface sediments, especially in low-latitude oceans, appears to be controlled by several environmental variables. The existence of multiple environmental controls may introduce biases in SST estimates for past oceans. In this study, the validity of SST

Fig. 1. (left) A strategy for comparing and evaluating quantitative faunal sea-surface temperature estimates. (a) A Pacific map presents site locations of a newly compiled test set of coretops (N = 132; big dots (•) or triangles (Δ) shown in shaded area that delineate the 20°N-30°S and 140°E-70°W low-latitude Pacific) and of a calibration set of coretops (N = 499; shown by small dots (•)) from a global data base (Prell, 1985). Within the shaded area, the 132 coretop test set is shown by different legends which indicate different levels of carbonate preservation ("•" indicating well-preserved [WPF/WPF+FRAGM% ≥ 60]) and "Δ" indicating highly dissolved [WPF/WPF+FRAGM% < 60] samples). (b) Bathymetric profiles of the carbonate preservation index (CPI% = WPF/WPF+FRAGM; RSP% = abundance of dissolution-resistant species as defined by Cullen and Prell (1984)) for the 132 coretop test set in the western, central, and eastern Pacific. The positions of foraminiferal lysoclines (FL [shaded]) approximately correspond to the changes in slopes of the CPI% or RSP% profiles. Lists of references for previously reported lysocline are given below. Over the western and central Pacific, samples with CPI% < 60 or RSP% >30 (indicated by arrows on the horizontal axes) are situated below the FL and are subjected to significant dissolution. Five coretops were identified as non-Recent ones from comparisons of coretop preservation with the depth of FL.

estimation for an independent test set of newly compiled coretop data is assessed using a calibration coretop data base previously collected from the Pacific Ocean (Prell, 1985). With the hope of identifying a more reliable approach when using paleoestimation methods to predict downcore environmental conditions, the present study proposes to:

(1) examine a test set of newly compiled coretop data (Figure 1a) which contains faunal compositions, carbonate preservation measures (CPI), and seasonal SST and DOT observations from the low-latitude Pacific;

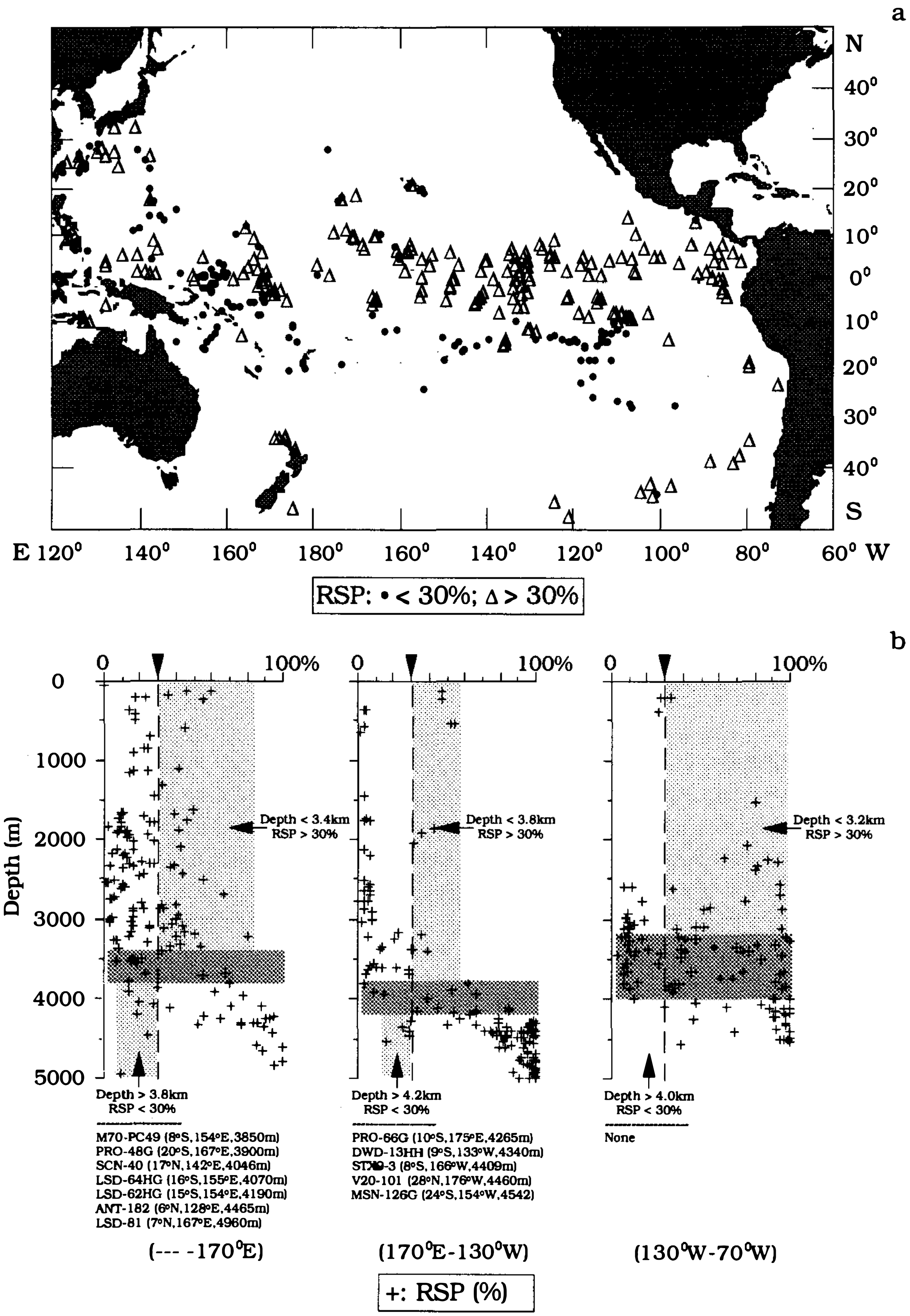
(2) screen the test data set and a calibration data set from the Pacific (Prell, 1985) (Figure 1a; 2a) and identify data that are suspected non-Recent or no-analogue samples (Figure 1b; 2b);

(3) develop standard versions of the IKM transfer functions for estimating SST and DOT based on the calibration data set, use the IKM transfer functions to compute SST estimates for the test set, and compare the true values and estimated values of the SST for the test data set; and

(4) identify possible sources of bias by comparing the residuals of the estimated SST and DOT with the surface ocean modes and with CPI.

3. DATA COMPILATION

Two sets of coretop data from the low-latitude Pacific were compiled and analyzed in this study. These coretop data include a calibration set (N = 417) from Prell (1985)'s compilation



for a Pacific data base of 499, and a test set (N = 132) compiled in this study. The 417 calibration coretop set was formed by eliminating 82 coretops from the 499 original data set.

Fig. 2. (left) An evaluation of a calibration set of coretops in the Pacific Ocean. (a) A Pacific map presents site locations of a calibration set of coretops (N = 405; shown by "•" indicating well-preserved [RSP% < 30%] and "Δ" indicating highly dissolved [RSP% > 30%] samples), a subset from a global data base (Prell, 1985). (b) Bathymetric profiles of the RSP% for the 405 coretops in the western, central, and eastern Pacific. The positions of foraminiferal lysoclines (FL) approximately correspond to the changes in slopes of the RSP% profiles. Over the western and central Pacific, samples with RSP% >30 (indicated by arrows on the horizontal axes) are situated below the FL and are subjected to significant dissolution. Twelve suspected non-Recent coretops that are situated below the FL, had abnormally low RSP% in the western and central Pacific.

The faunal compositions of these 82 coretops are dominated by subpolar-polar species (Globigerina pachyderma (left coiling)) which are rarely found in the low-latitude oceans. The test set coretop data (N = 132) were collected from Thompson (1977) as well as from some unpublished counts generated at Brown University (N.G. Kipp, W.L. Prell, M.-T. Chen, and V.S. McKenna) (Chen, 1994a). This test set of coretops was selected from the low-latitude Pacific (140°E to 70°W and by 20°N to 30°S), with greater concentrations from the eastern and western equatorial regions (Figure 1a). The test set incorporates planktonic foraminifer faunal assemblages from various ocean environments. This test set also contains counts of foraminifer fragments which were used to quantitatively evaluate the effect of carbonate preservation (Chen, 1994a).

The uses of a taxonomic scheme of planktonic foraminifers, indices of carbonate preservation (CPI = [whole planktonic foraminifers / (whole planktonic foraminifers + planktonic foraminifer fragments)]) and resistant species ratio (RSP%, Cullen and Prell, 1984), and extraction of environmental data of upper-layer oceans (SST and DOT) from a NOAA compilation (Levitus, 1982; 1987) were described in Chen (1994a; b).

4. CORETOP EXAMINATION AND SCREENING

Reconstructions of past SST based on marine microfossils require using a set of coretops that contain the most recently deposited sediments. In paleoestimation, contamination by non-Recent coretops could lead to significant yet undetectable biases. While direct age-controls for the coretops are lacking in this study, indirect criteria were used to judge whether the coretops are modern sediments. Water depth variations in preservation indices from test set coretops show a distinct change in preservation at the depth of the foraminiferal lysocline (FL), which can be compared to the depth of the previously reported regional lysocline (Figure 1b). Pacific glacial sediments that lie above the FL are characterized by good preservation. Thus coretops that are well preserved but are found below the FL are presumed to be non-Recent samples. Poorly preserved coretops that are found above the FL could have resulted from an anomalous calcium carbonate saturation state or from increased winnowing. In either case, such samples should be excluded from the analyses. Examining 132 test data based on these criteria, five coretops from the test set were identified as having deviating values for whole planktonic foraminifer ratios and were eliminated in further analyses (Figure 1b).

The calibration data set was screened in the same way except only RSP% was used to indicate sample preservation (Figure 2b). By this method, 12 of the remaining 417 samples were identified as either non-Recent or containing anomalous sediments, and thus were excluded from the analyses.

5. CALIBRATION SET EVALUATION: THE DEVELOPMENT OF TRANSFER FUNCTIONS

To study how faunal estimates of SST might be biased by specific environmental controls (e.g. upper-layer ocean conditions or preservation), transfer functions were developed by applying the standard procedures of the IKM (Imbrie and Kipp, 1971; Kipp, 1976) and the MAT (Prell, 1985). Eight faunal factors (LP1 to LP8) were analyzed from a Q-mode factor analysis (VARIMAX solution) using 405 calibration coretops (Table 1, Figure 3a-h). The first four of the eight factors represent almost 85% of the variance of the original faunal data, and the last four are ecologically meaningful species that are highly relevant in paleoestimation. These eight factors explain 97% of the variance of the data and their first-order distribution patterns appear to be associated with Pacific SST or DOT patterns (Chen, 1994a). For example, the abundances of G. ruber (LP1), G. glutinata (LP6), and G. sacculifer (LP7) are at a maximum in both the western Pacific and central gyres, which are regions where the oceanic conditions are characterized by a relatively warm SST and deep DOT with little seasonal variability. The abundances of G. tumida (LP2), N. dutertrei (LP3), P. obliquiloculata (LP4), and G. menardii (LP8) , however, dominate the equatorial divergence and coastal upwelling zones, where the SST is relatively cold and the DOT is shallow. Moreover, G. bulloides (LP5) is most abundant in subpolar regions where the SST is cold and shows large seasonal variations.

In computing regression coefficients (Table 2), linear and curvilinear terms for faunal factor loadings from a calibration set of 405 coretops were used to generate transfer functions for estimating the SST. The relationships expressed by these transfer functions may be more appropriate for this data set because faunal variations in the Pacific are primarily nonlinear. Observations of SST-cold season were used because they are characterized by a large range of variation and have been conventionally used for downcore estimation in many previous studies. The SST transfer function had a correlation coefficient of 0.88 and a standard error of 1.92°C (Figure 4; Table 2).

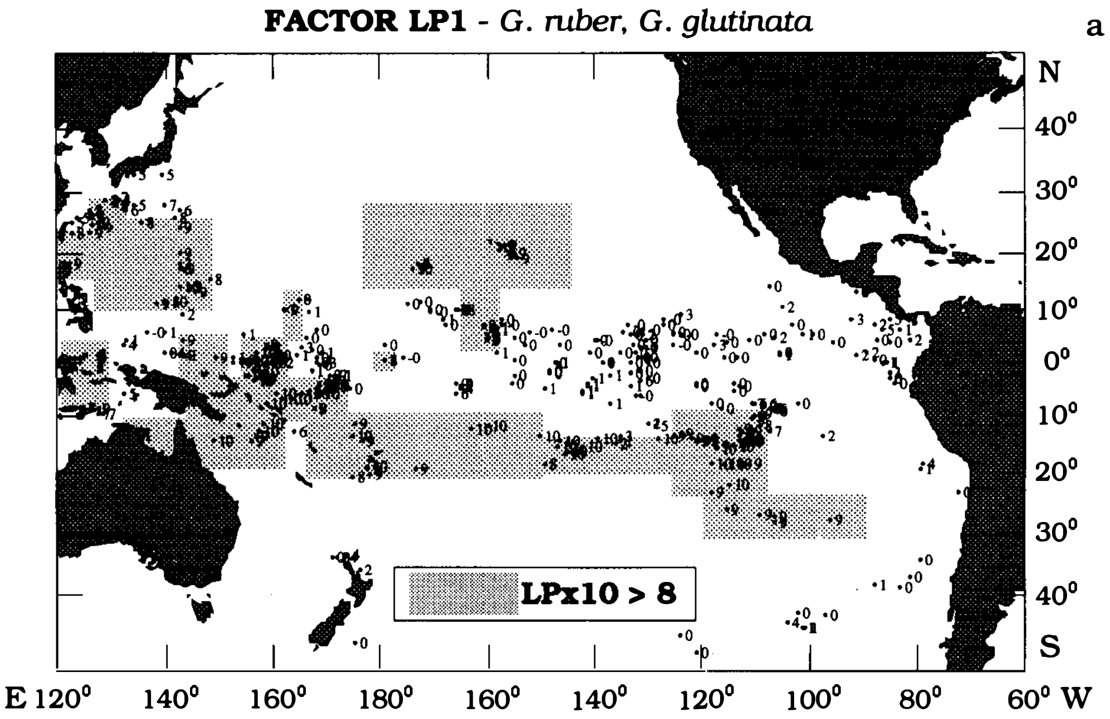
A standard version of the IKM was also used to generate a transfer function for extracting DOT information from planktonic-foraminifer abundance data. It should be noted that this analysis was confined to the annual mean DOT since seasonal DOT changes are not commonly coupled with seasonal surface temperatures. While seasonal variations in DOT are an important component in analyzing upper-layer ocean structure (McIntyre *et al.*, 1989; Ravelo *et al.*, 1990), with the variations increasing over high latitudes and in coastal oceans, these variations are not relevant to the present study. The Pacific DOT transfer function had a multiple correlation coefficient of 0.90 with a standard error of about 28.11 m (Table 3; Figure

Table 1. Factor score-assemblage matrix (F) (VARIMAX solution) for 405 calibration faunal data of low-latitude Pacific (LP) coretops.

Foraminifer Species-Variable	LP1	LP2	LP3	LP4	LP5	LP6	LP7	LP8
Orbulina universa	0.015	0.002	-0.001	-0.003	0.046	0.000	0.026	0.031
Globigerinoides conglobatus	0.083	0.015	-0.012	0.011	0.019	-0.086	0.100	-0.019
Globigerinoides ruber	**0.779**	0.032	-0.024	-0.060	-0.005	-0.583	-0.114	-0.064
Globigerinoides tenellus	0.062	0.004	-0.002	-0.010	-0.015	-0.043	-0.042	-0.014
Globigerinoides sacculifer	0.219	-0.007	0.014	0.084	-0.016	0.111	**0.900**	0.039
Sphaeroidinella dehiscens	0.009	0.040	-0.006	0.003	0.001	0.010	0.024	0.037
Globigerinella aequilateralis	0.125	-0.013	-0.009	0.074	-0.016	0.025	0.243	0.050
Globigerina calida	0.083	-0.006	0.015	0.027	-0.046	0.060	-0.054	0.208
Globigerina bulloides	0.009	-0.020	-0.010	0.001	**0.867**	0.014	0.039	-0.023
Globigerina falconensis	0.014	-0.001	0.001	-0.002	0.061	-0.004	-0.043	-0.007
Globigerina digitata	0.010	0.007	0.001	0.003	0.011	0.011	0.016	0.002
Globigerina rubescens	0.064	0.003	-0.003	-0.008	-0.020	0.015	-0.050	-0.010
Globigerina pachyderma L.	-0.016	0.007	-0.015	-0.005	0.185	0.007	0.017	0.013
Globigerina pachyderma R.	0.003	-0.001	0.002	-0.001	0.031	-0.006	-0.005	-0.009
Neogloboquadrina dutertrei	0.011	-0.014	**0.996**	0.020	0.013	-0.021	-0.009	-0.072
Globoquadrina conglomerata	0.034	0.032	-0.001	0.032	-0.027	0.156	0.132	-0.037
Globoquadrina hexagona	0.007	0.003	0.001	0.001	-0.000	0.029	0.020	0.015
Pulleniatina obliquiloculata	0.022	-0.033	-0.024	**0.990**	0.011	-0.046	-0.109	-0.015
Globorotalia inflata	-0.012	0.003	-0.002	-0.015	0.427	-0.032	-0.027	0.059
Globorotalia truncatulinoides L.	0.001	0.002	-0.001	-0.002	0.002	-0.006	-0.003	0.007
Globorotalia truncatulinoides R.	0.009	0.006	-0.002	-0.010	0.137	-0.049	-0.021	0.035
Globorotalia crassaformis	0.011	0.003	0.002	0.000	0.028	0.004	0.009	0.003
Globorotalia hirsuta	0.000	0.000	-0.000	-0.000	0.009	-0.002	-0.001	0.000
Globorotalia scitula	0.007	-0.001	-0.000	0.001	0.018	0.002	0.009	0.010
Globorotalia menardii	0.023	0.004	0.069	0.002	-0.003	-0.054	-0.040	**0.966**
Globorotalia tumida	-0.018	**0.997**	0.015	0.036	0.015	0.022	0.001	-0.002
Globigerinita glutinata	0.552	-0.010	0.008	-0.011	0.020	**0.774**	-0.250	0.002
VARIANCE	38.17	14.80	17.53	14.74	5.00	3.42	1.96	1.76
CUMULATIVE VARIANCE	38.17	52.97	70.50	85.24	90.24	93.66	95.62	97.38

4), indicating that about 81% of the original DOT variance is explained.

Plots comparing estimated and observed SST and DOT (Figure 4) clearly indicate that although the correlation coefficients were approximately the same, the DOT transfer function resulted in a more systematic relationship when compared to that for SST. The DOT data are more evenly distributed over the range of prediction than the SST data, which display a cluster of points confined within the temperature range of 20° to 30°C. This distribution of SST data can be deceptive, resulting in a positive correlation which appears stronger than the actual



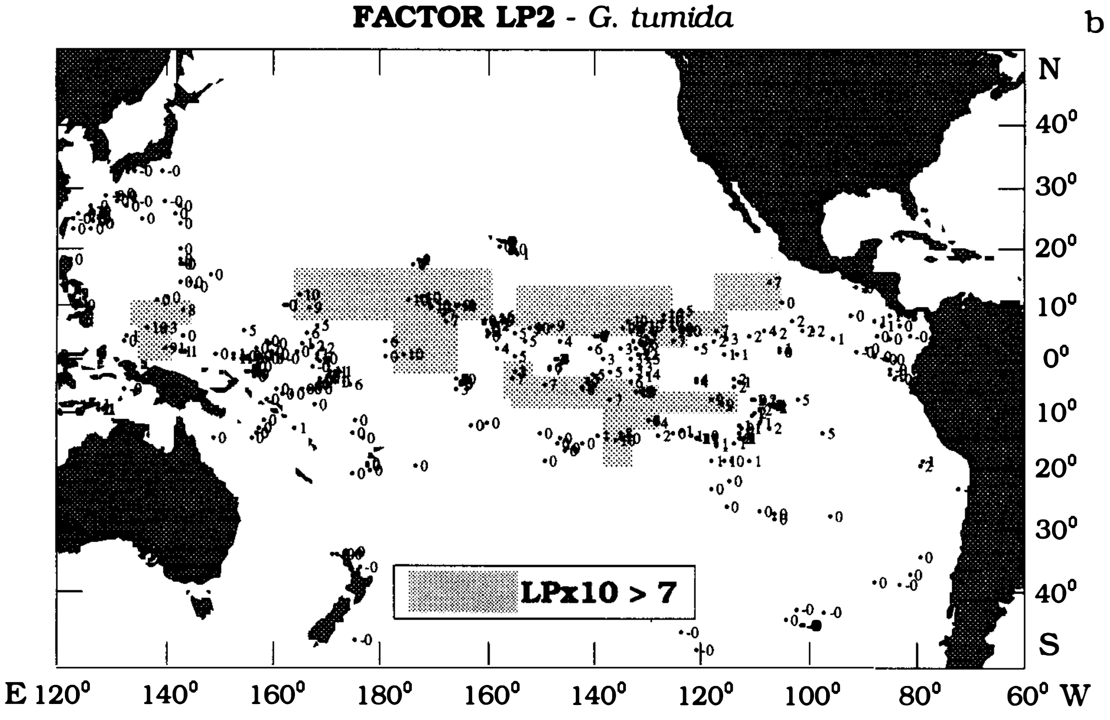


Fig. 3. Distributions of the abundances of eight dominant planktonic foraminifer factors in the low-latitude Pacific Ocean (data from 405 coretops of a calibration data set). The distribution patterns of some species are not well parallel to sea-surface temperatures. For example, G. ruber, N. dutertrei, G. glutinata, and G. menardii are distributed across a sharp gradient of sea-surface temperatures. These SST-insensitive faunas may introduce biases in paleoestimation.

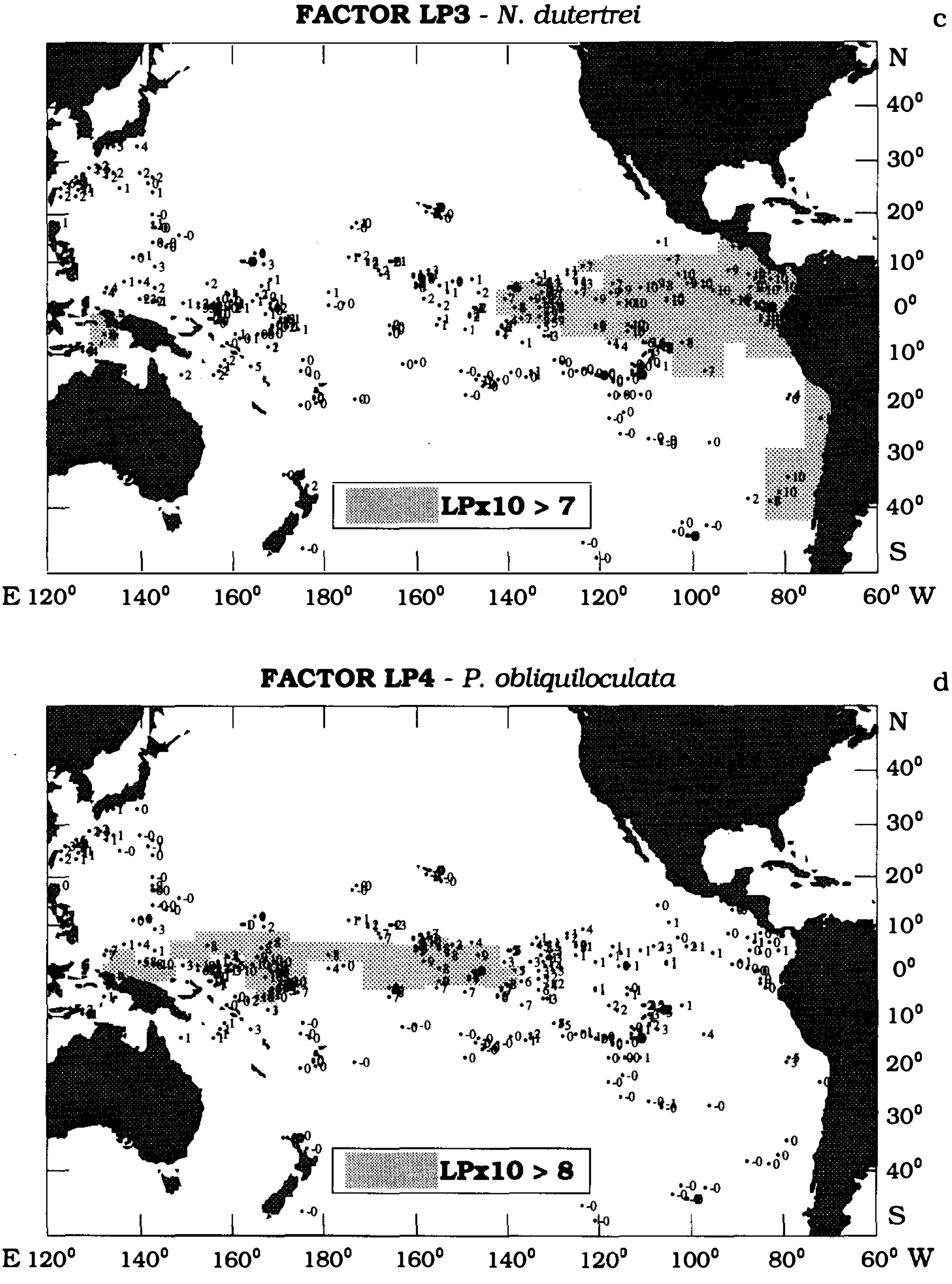
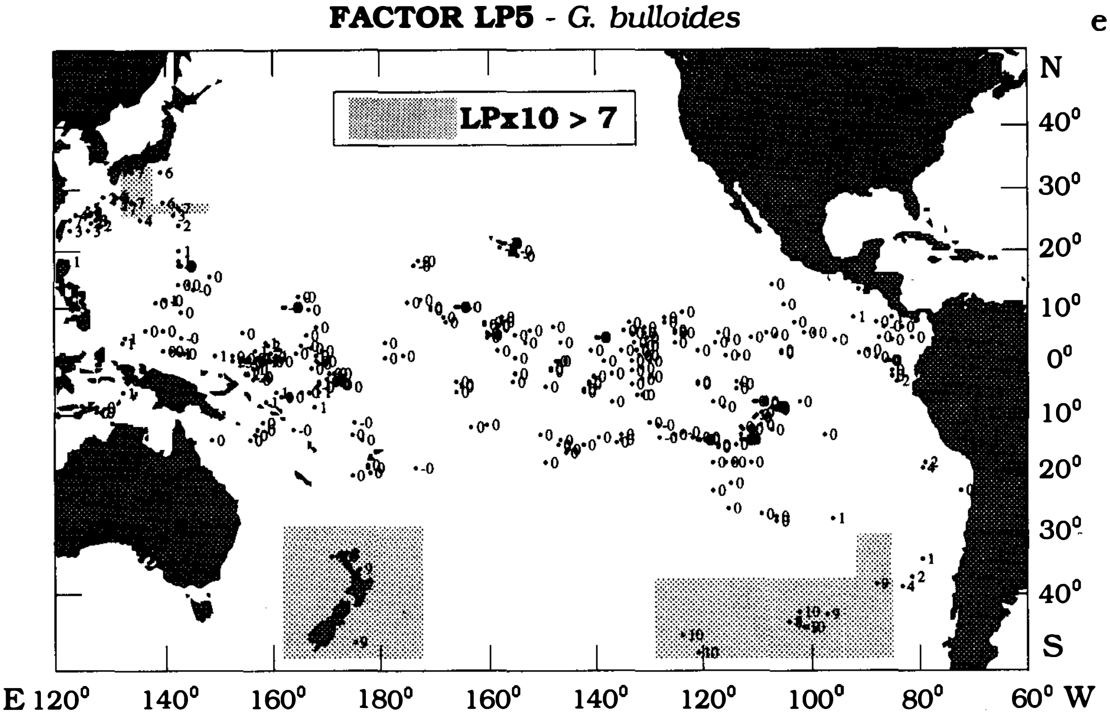


Fig. 3. (Continued)

relationship.

Since multiple regression is an important component in transfer functions, the residuals of the SST estimates (ΔSST = estimated SST - observed SST) for the calibration data should be analyzed in various ways in order to detect possible anomalies. Residuals are by definition independent of the linear effects of predicted values. Plots of residual and estimated SST and

FACTOR LP5 - *G. bulloides*



FACTOR LP6 - *G. glutinata, G. ruber(-)*

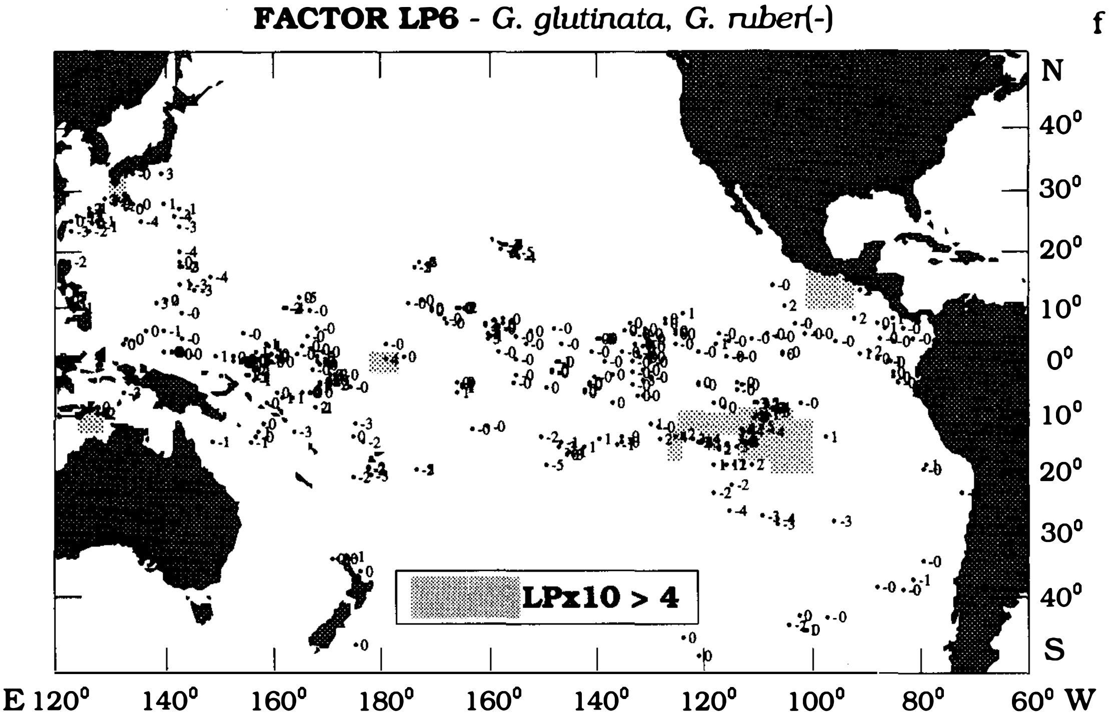
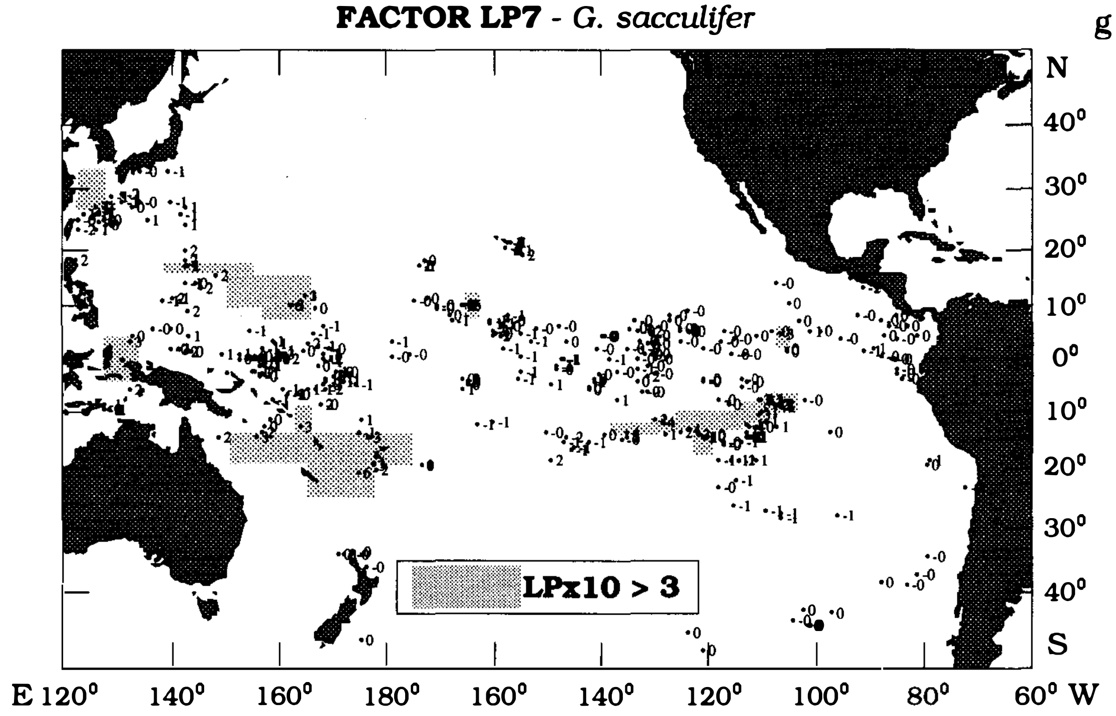


Fig. 3. (Continued)

DOT from the 405 coretops reveal them to have linear independent relationships with no major anomalies (Figure 5). On the other hand, residuals should not be correlated with the dependent variable (observed value), which would imply that the regression model is underspecified and omits relevant predictors. For instance, plots of residual and observed SST and DOT from the 405 coretops revealed linear trends (Figure 6). In these plots, the transfer

FACTOR LP7 - *G. sacculifer*



FACTOR LP8 - *G. menardii*

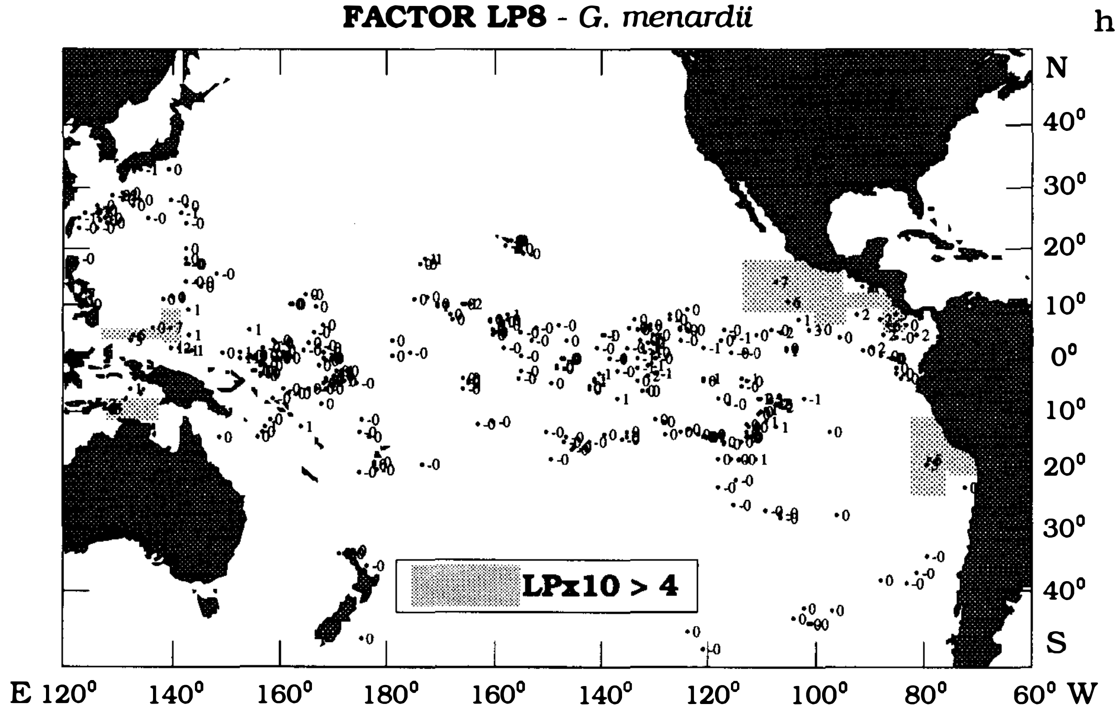


Fig. 3. (Continued)

functions predicted biased estimates, with tendencies toward higher estimates for low values and lower estimates for high values. This suggests that other environmental variables may play roles in controlling variations in the faunal terms.

The above analyses demonstrate that the correlative relationship of the distribution of planktonic foraminifers with DOT is more significant than that with SST, and indicates that

Table 2. Imbrie-Kipp transfer functions for estimating low-latitude Pacific (LP) sea-surface temperatures based on 405 low-latitude Pacific coretops.

Sea-Surface Temperature (SST)-cold season	
Variable	Regression Coefficient
LP5-SQ	9.651
LP3-SQ	5.376
LP6-SQ	0.842
LP6-LP7	-8.742
LP1-LP4	-4.784
LP1-LP2	-36.263
LP4-LP5	-37.868
LP3-LP8	-4.199
LP7-SQ	3.256
LP2-LP3	-9.131
LP4-LP6	-17.868
LP1-LP6	10.886
LP3	11.853
LP2-LP6	-8.562
LP5-LP7	40.510
LP1-LP5	2.015
LP5	-6.134
LP3-LP5	-5.183
LP5-LP6	17.540
LP4	24.789
LP1-LP3	-12.249
LP5-LP8	5.047
LP1-LP8	-24.183
LP3-LP7	-15.241
LP1-LP7	-16.229
LP2	25.244
LP7	13.509
LP1-SQ	-6.049
LP2-LP4	-16.657
LP3-LP4	-14.526
LP1	28.936
LP8	25.507
LP4-LP7	-9.519
LP2-LP7	-6.904
LP2-LP5	-20.071
LP4-LP8	-9.545
LP3-LP6	5.937
LP6	-10.063
LP2-LP8	-12.733
LP8-SQ	-8.059
LP6-LP8	6.642
LP2-SQ	-2.850
LP4-SQ	-2.536
LP7-LP8	1.876
INTERCEPT	4.018

Multiple Correlation Coefficient
(adjusted for degrees of freedom) = 0.884

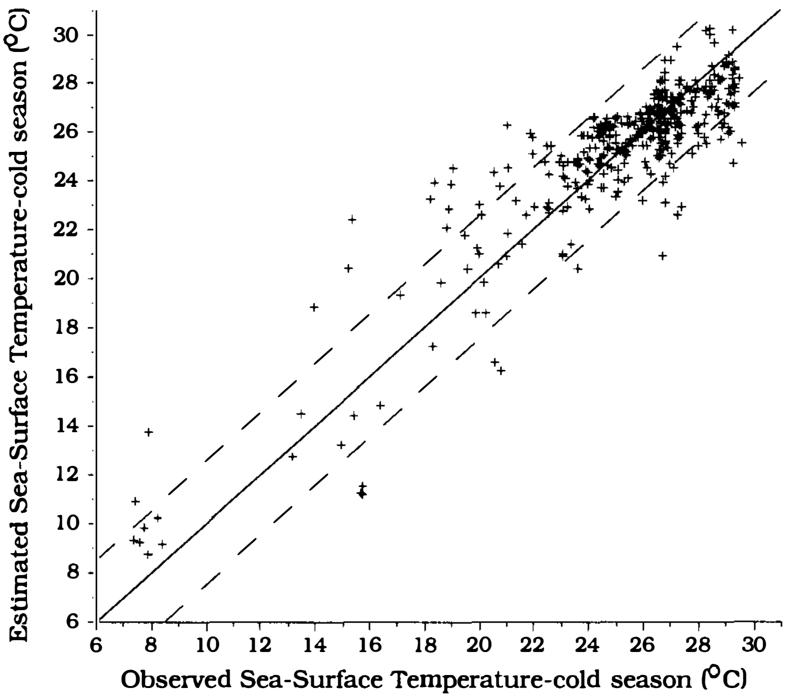
Standard Error of Estimate
(adjusted for degrees of freedom) = 1.921

Table 3. Transfer function for estimating low-latitude Pacific (LP) annual average depth of thermocline (DOT).

Depth of Thermocline (DOT)	
Variable	Regression Coefficient
LP3	113.700
LP1	601.344
LP4-LP5	569.768
LP1-LP8	-259.934
LP5-SQ	-394.466
LP5-LP8	-391.304
LP6-SQ	-426.771
LP2-LP6	-201.316
LP1-SQ	-501.303
LP1-LP3	-219.615
LP1-LP4	-376.598
LP3-LP4	-150.159
LP5-LP7	-209.669
LP3-LP8	-140.785
LP4-LP8	139.837
LP2-LP8	-167.876
LP7-LP8	-178.723
LP1-LP6	332.712
LP6	-306.012
LP2-LP7	-254.593
LP8-SQ	-109.117
LP3-LP6	113.758
LP1-LP5	-113.957
LP3-LP7	-192.892
LP7-SQ	-369.402
LP2-LP5	-915.601
LP2-LP3	-190.668
LP3-SQ	-228.320
LP7	550.935
LP1-LP7	-555.679
LP4-LP7	-248.544
LP6-LP8	171.748
LP2-SQ	-388.433
LP4-SQ	-360.107
LP2	403.683
LP2-LP4	-290.296
LP4	378.607
LP1-LP2	-230.156
LP3-LP5	-166.058
LP5	205.533
LP5-LP6	122.069
LP6-LP7	54.465
LP8	8.298
LP4-LP6	4.334
INTERCEPT	141.926

Multiple Correlation Coefficient
(adjusted for degrees of freedom) = 0.900

Standard Error of Estimate
(adjusted for degrees of freedom) = 28.110



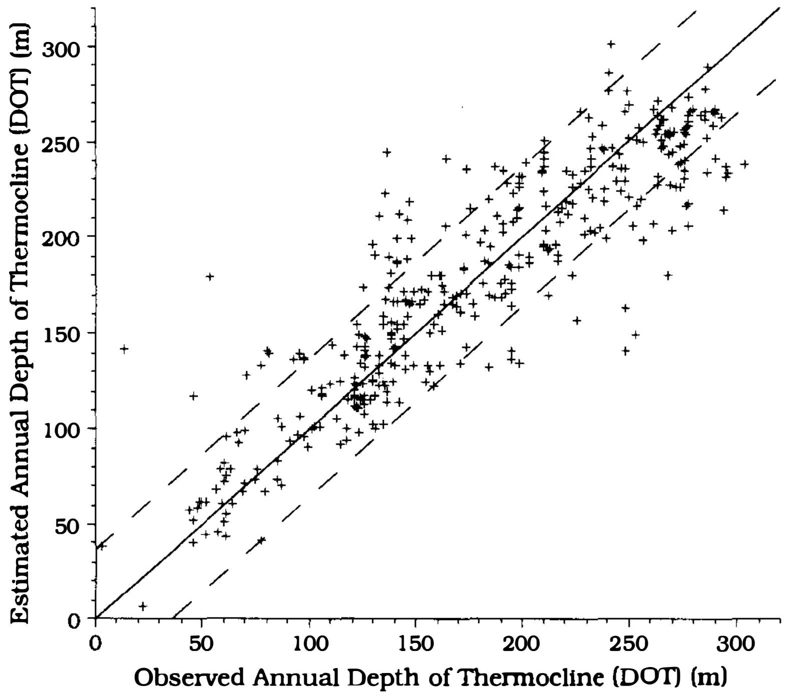


Fig. 4. Scatter diagrams comparing observed and estimated SST-cold season and observed and estimated annual average DOT. Estimations were predicted using transfer functions (equations shown in Table 2 and 3) which relate eight foraminifer faunal factors to the oceanographic observation data from 405 low-latitude Pacific coretop data (Chen, 1994). Fifteen coretops were not used in the analysis because either the DOT could not be defined (SST ≤ 18°C) or subsurface temperature data was missing. The dashed lines show the boundaries at the 80% confidence level.

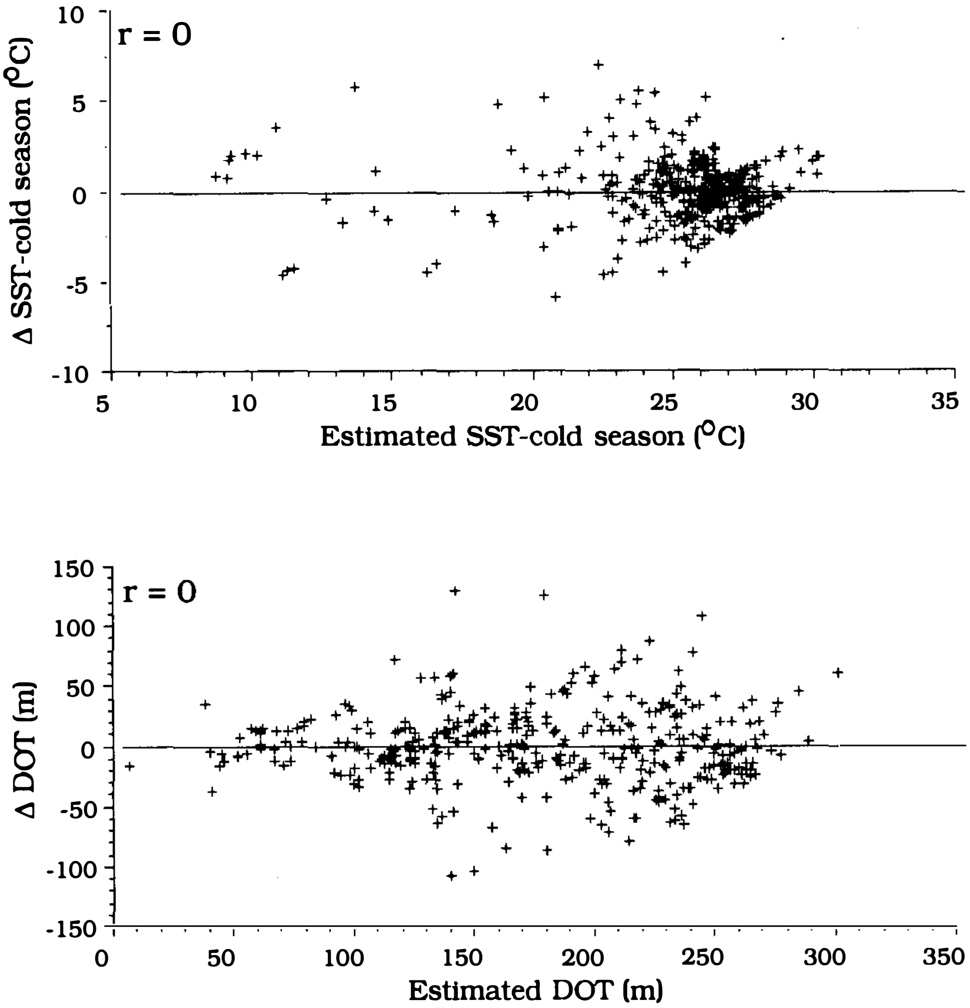


Fig. 5. Scatter diagrams comparing estimated SST with ΔSST (= estimated SST - observed SST) and estimated DOT with ΔDOT predicted by the IKM transfer functions for 405 coretops in the low-latitude Pacific during cold and warm seasons. The correlation coefficients (r = 0) and lines in these plots were obtained from simple linear regression analyses.

the faunal data can be applied to fossil records to systematically reconstruct DOT in paleoenvironments. Many previous studies have suggested that changes in faunal abundances in relation to SST are indirect responses to the more direct influence of DOT (Bé and Tolderlund, 1971; Fairbanks and Wiebe, 1980; Fairbanks *et al.*, 1980; Williams and Healy-Williams, 1980; Deuser *et al.*, 1981; Fairbanks *et al.*, 1982; Curry *et al.*, 1983; Thunell and Reynolds, 1984; Deuser, 1987; Deuser and Ross, 1989; Ravelo *et al.*, 1990). When the DOT becomes deep, the relative abundance of the shallow-dwelling species increases as a result of the deep-dwelling species being forced to migrate into aphotic zones where photosynthesis by phytoplanktons is prohibited; and when the DOT becomes shallow, the abundance of faunal species that prefer living in the deeper portion of the upper-layer increases due to higher levels of photosynthesis and nutrient supply in the photic zone. This DOT transfer function could strengthen interpretations of surface ocean variability based on late Quaternary deep-sea records. If DOT condi-

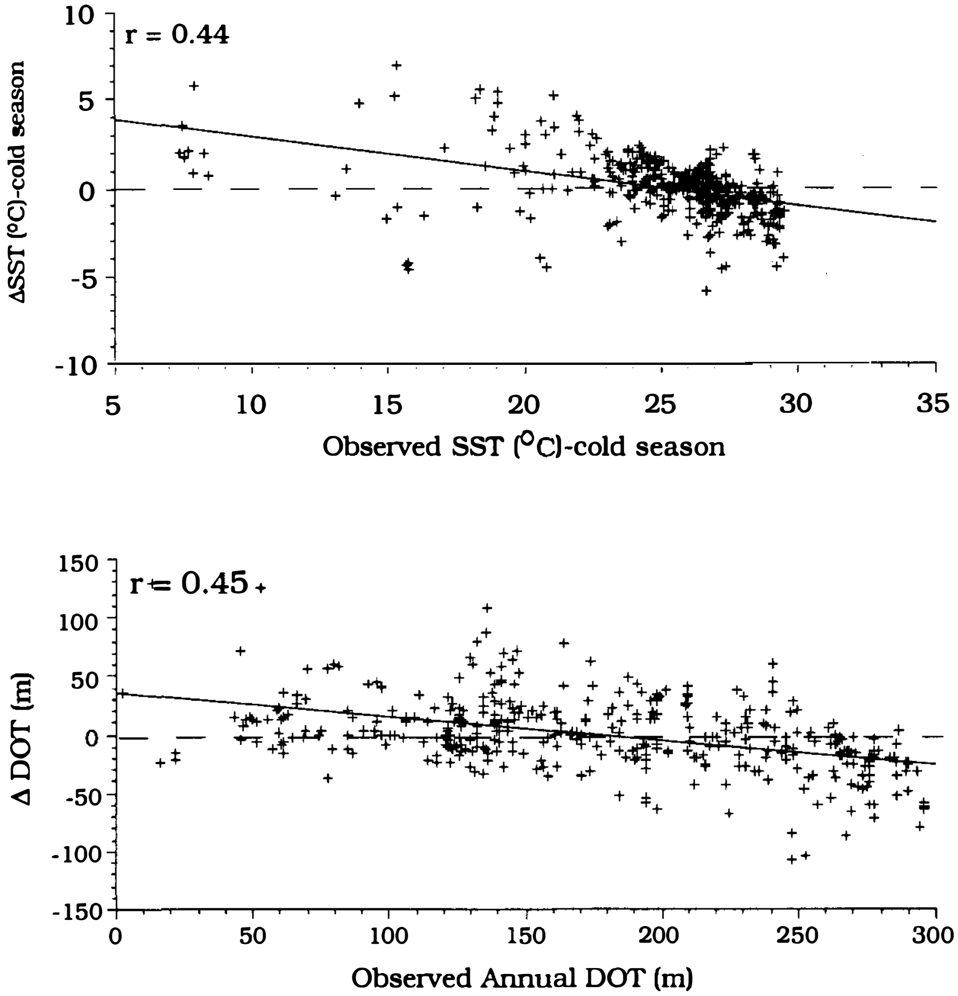


Fig. 6. Scatter diagrams comparing observed SST with ΔSST (= estimated SST - observed SST) and observed DOT with ΔDOT as predicted by the IKM transfer functions for 405 coretops in the low-latitude Pacific during cold and warm seasons. The correlation coefficients (r) and lines in these plots were obtained from simple linear regression analyses.

tions and the correlative relationship between SST and DOT in the low-latitude oceans have changed since the LGM, as has been suggested (Ravelo *et al.*, 1990), then faunal-derived SST estimates may be biased. Such biases need to be assessed and SST values reevaluated, based on the interrelationships that exist between SST and other environmental factors in the low-latitude Pacific.

6. TEST SET EVALUATION: A SURFACE OCEAN MODE ANALYSIS

To address the issue of whether the effects of other variables can generate biases in SST estimates, it was assumed that these environmental factors, including upper-layer ocean conditions and carbonate preservation state, are intercorrelated in the low-latitude Pacific. In which case, faunal estimates of SST may be made indirectly through the effects of one or more related environmental controls. The above analyses of surface ocean modes in the modern

Table 4. Two surface ocean modes#. Principal component scores and loadings matrices computed using principal component analysis## for observed SST and DOT from 132 low-latitude Pacific coretop sites.

Core ID	Mode 1	Mode 2	Core ID	Mode 1	Mode 2	Core ID	Mode 1	Mode 2
DSDP572 MTC	-0.88	0.44	RC13-027 NGK	0.33	0.24	V24-048 PRT	-0.92	0.69
ODP847B VSM	-1.42	0.70	RC13-063 PRT	0.07	0.50	V24-048 NGK	-0.92	0.69
M70-PC44 PRT	1.27	0.01	RC13-108 PRT	-1.79	0.12	V24-055 PRT	-0.37	0.48
RC08-093 PRT	-1.81	-1.53	RC13-108 NGK	-1.79	0.12	V24-056 PRT	-0.30	0.47
RC08-093 NGK	-1.81	-1.53	RC13-113 NGK	-1.44	0.50	V24-057 PRT	-0.22	0.52
RC09-077 PRT	-2.38	-0.64	RC13-122 PRT	-0.28	1.66	V24-061 PRT	0.07	0.76
RC09-077 NGK	-2.38	-0.64	RC13-139 NGK	-0.82	1.55	V24-108 PRT	0.89	1.09
RC09-104 PRT	-0.90	-1.28	RC17-179 PRT	0.69	1.00	V24-157 DMA	1.18	-0.31
RC09-104 NGK	-0.90	-1.28	RC17-180 PRT	0.81	1.04	V24-158 DMA	1.26	-0.36
RC09-121 PRT	-0.32	-1.71	RC17-181 PRT	0.62	0.94	V24-161 DMA	1.02	-0.92
RC09-121 NGK	-0.32	-1.71	RC17-182 PRT	0.60	0.97	24-166 DMA	1.16	-0.63
RC09-124 PRT	-1.17	-1.48	V15-029 NGK	-0.47	1.98	V24-167 DMA	1.22	-0.43
RC09-124 NGK	-1.17	-1.48	V18-272 PRT	1.33	-0.17	V24-168 DMA	1.21	-0.49
RC10-054 NGK	-0.72	1.65	V18-312 PRT	-0.89	0.30	V24-170 DMA	1.10	-0.19
RC10-114 PRT	1.34	-0.03	V18-318 PRT	-0.77	0.38	V24-171 DMA	1.17	-0.37
RC10-115 PRT	1.31	0.09	V18-350 PRT	-0.52	1.91	V24-172 DMA	1.21	-0.30
RC10-131 DMA	1.16	-0.44	V19-025 PRT	-0.93	1.54	V24-179 DMA1	1.22	-0.43
RC10-135 DMA	1.04	-0.23	V19-029 NGK	-1.95	-0.03	V24-179 DMA2	1.22	-0.43
RC10-144 PRT	1.06	1.24	V19-030 PRT	-1.95	-0.03	V24-181 DMA	1.05	-0.81
RC10-149 PRT	0.57	1.45	V19-040 NGK	-1.38	-0.82	V24-183 DMA	1.26	-0.36
RC11-209 PRT	-0.07	0.72	V19-041 PRT	-1.27	-1.13	V24-184 DMA	0.95	-0.04
RC11-210 PRT	-0.21	0.49	V19-041 NGK	-1.27	-1.13	V28-148 PRT	-0.91	1.38
RC11-211 PRT	-0.36	0.33	V19-045 PRT	-0.06	-1.37	V28-148 NGK	-0.91	1.38
RC11-213 PRT	0.36	0.15	V19-053 NGK	0.17	-1.26	V28-195 PRT	-0.07	1.07
RC11-217 PRT	1.19	-0.42	V19-055 PRT	0.22	-1.23	V28-201 PRT	0.54	0.78
RC11-220 PRT	1.08	-0.76	V19-055 NGK	0.22	-1.23	V28-211 PRT	1.38	-0.06
RC11-227 NGK	-0.78	0.16	V19-064 PRT	0.41	-1.13	V28-212 PRT	1.20	-0.41
RC11-230 PRT	-0.62	-0.10	V19-064 NGK	0.41	-1.13	V28-222 PRT	1.35	0.08
RC11-230 NGK	-0.62	-0.10	V19-065 PRT	0.46	-1.13	V28-227 PRT	1.32	0.33
RC11-232 NGK	-0.71	-0.50	V19-065 NGK	0.46	-1.13	V28-227 DMA	1.32	0.33
RC11-237 NGK	-1.69	0.42	V19-088 PRT	1.53	-0.13	V28-236 PRT	1.22	1.16
RC11-238 NGK	-1.69	0.42	V19-096 NGK	0.83	0.85	V28-237 PRT	0.86	1.04
RC12-107 PRT	-0.49	-1.69	V19-097 PRT	0.78	0.89	V32-093 PRT	-0.43	1.99
RC12-107 NGK	-0.49	-1.69	V19-098 PRT	0.69	1.00	V32-098 PRT	-0.75	1.02
RC12-109 DMA	0.17	-2.03	V19-099 PRT	0.67	1.10	V32-099 PRT	-0.75	0.46
RC12-113 PRT	0.13	-2.10	V21-039 PRT	-1.01	0.17	V32-100 PRT	-0.67	0.62
RC12-113 NGK	0.13	-2.10	V21-041 PRT	-1.03	0.06	V32-101 PRT	-0.60	0.63
RC12-113 DMA	0.13	-2.10	V21-041 NGK	-1.03	0.06	V32-102 PRT	-0.30	0.47
RC12-122 PRT	0.64	0.90	V21-042 NGK	-0.91	0.15	V32-103 PRT	-0.02	0.89
RC12-123 PRT	0.71	1.00	V21-051 NGK	0.67	-0.72	V32-109 PRT	0.10	0.97
RC12-124 PRT	0.83	1.20	V21-053 PRT	1.01	-1.07	V32-172 PRT	0.65	1.01
RC12-210 PRT	-0.29	-1.85	V24-040 NGK	-0.85	1.45	V32-175 PRT	1.32	0.21
RC12-210 NGK	-0.29	-1.85	V24-041 NGK	-1.08	0.92	V33-119 PRT	1.21	-0.32
RC13-017 NGK	0.36	-0.44	V24-047 NGK	-0.98	0.92	V34-002 PRT	0.96	-0.86

	Mode 1	Mode 2
SST-cold season	0.77	0.60
SST-warm season	0.87	0.43
DOT-cold season	0.87	-0.46
DOT-warm season	0.82	-0.54

Surface ocean mode 1 explains 70% variance and mode 2 explains 26% variance in the raw data.
Principal component analysis (PCA) was performed by extracting eigenvectors from correlation matrix.

low-latitude Pacific can be further explained by the fact that DOT and SST are coupled by two climatic processes which are statistically independent. Moreover, since the IKM and MAT are quantitative techniques which predict the average condition based on the entire set of data samples, the collective use of all calibration data from the low-latitude Pacific may also give biased estimates.

Conditions in the upper-layer oceans where the 132 test coretops are located were examined using a principal component analysis for four variables: SST-cold season, SST-warm season, DOT-cold season, DOT-warm season (Table 4). The first component represents the surface ocean mode in which the SST and DOT are positively correlated (mode 1), and the second component represents the mode in which the SST and DOT are negatively correlated (mode 2). High scores for the first component (high SST and deep DOT) occur everywhere in the low-latitude Pacific, except in the eastern equatorial region. The scores of the second component (high SST and shallow DOT) are distributed as a dipole along the equatorial zone with the maximum scores at the eastern and western extremes (Figure 7).

These two linearly independent surface ocean modes are probably controlled by an interaction of atmospheric and upper-layer ocean processes. The vertical heat flux through the thermocline is commonly assumed to be important to the heat budget of upper-layer oceans. A shallow thermocline causes cooling in surface oceans which in turn decreases the SST. Thus the predominance of the positively correlated mode 1 implies an obvious connection between SST and DOT through this mechanism, which is probably driven by the convergence and divergence of the upper-layer waters in the low-latitude Pacific. The zonal component of the trade winds, termed “Walker Circulation”, converges warm surface waters in the western Pacific, and exposes cold subsurface waters in the eastern Pacific. The negative correlation between SST and DOT in mode 2 implies only a limited influence from upper-layer ocean dynamics on SST fluctuations, or a decoupling of SST and DOT. The zonal pattern of this mode suggests a linkage to the trade wind forces of the low-latitude Pacific, which are perhaps driven by the seasonal displacement of the Intertropical Convergence Zone (ITCZ) (Philander, 1990). During the northern hemisphere summer, when the ITCZ is displaced to the north, incoming solar insolation is minimal south of the ITCZ, which results in a lower SST. Meanwhile, the southeast trade winds become stronger and increase air-sea heat exchange and in turn deepen the DOT in the southern hemisphere. All of these conditions are reversed during the northern hemisphere winter. The southernmost position of the ITCZ accompanied by maximum solar radiation and weaker winds, results in higher SST and shallower DOT in the southern hemisphere. For these reasons, SST and DOT in mode 2 are negatively correlated.

If faunal abundances of planktonic foraminifers are primarily controlled by DOT changes and faunal estimates of SST are made indirectly through the effects of DOT, the use of calibration data that contain additional correlative relationships between SST, DOT, and other variables could generate biases. To test this possibility, the residuals of the SST estimates (ΔSST) of the 132 test coretops were analyzed in scatter plots in which the ΔSST was plotted against several factors, including the principle components of sea-surface conditions that represent the modes of upper-layer ocean conditions as well as CPI (Figure 8). Because non-Recent and no-analogue coretops would be estimated with large errors, 17 test coretops which were previously identified when testing the significance of the relationships between SST and these other

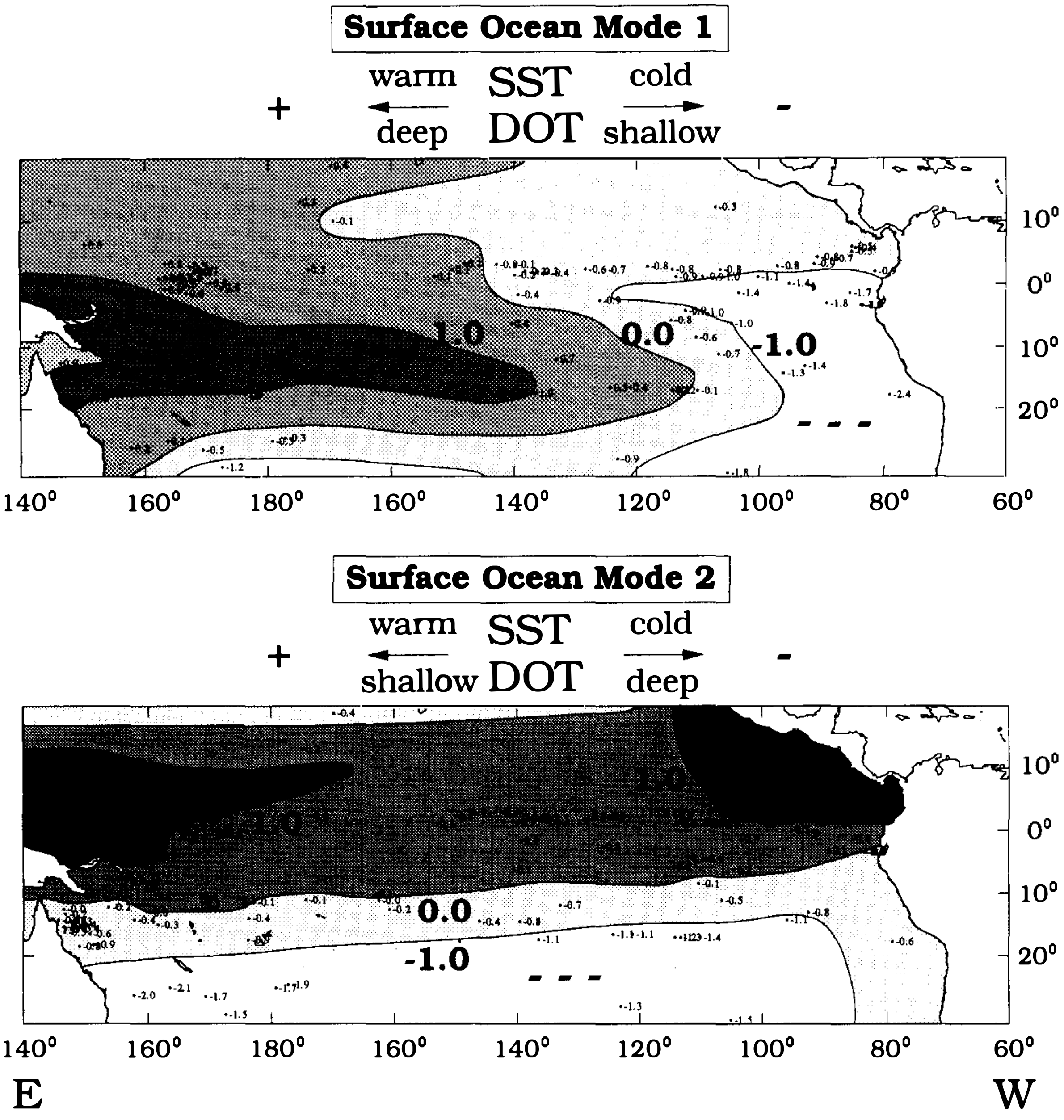


Fig. 7. Distribution of two surface ocean modes. A principal component analysis (PCA, see Table 5) is used to analyze the relationship between SST and DOT from 132 low-latitude Pacific coretop data. Mode 1, in which high SST is correlated with deep DOT, reaches a maximum near the equator, with positive scores in the western and negative scores in the eastern Pacific. Mode 2, in which high SST is correlated with shallow DOT, is a dipole with positive scores over the equator and negative scores away from the equator and nodes near the northernmost and southernmost extremes of the Intertropical Convergence Zone (ITCZ). The patterns of the two surface ocean modes are driven by different climatic mechanisms. The predominance of mode 1 suggests that thermocline dynamics play an important role in SST variations in the low-latitude Pacific .

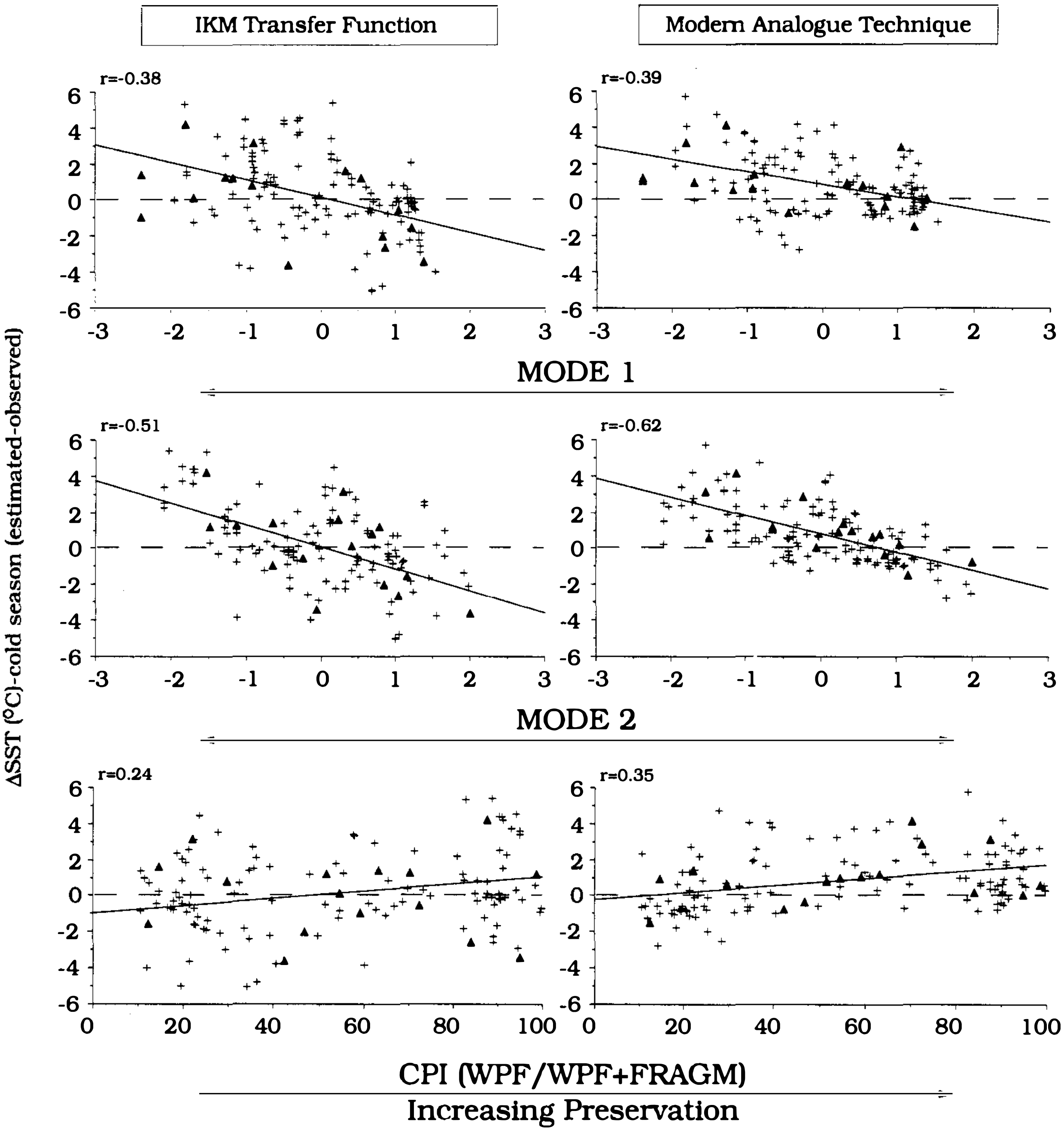


Fig. 8. Residual analyses for examining estimated SST biases that are caused by influences from other environmental controls. Scatter diagrams compare the relationships between ΔSST and two observed surface ocean modes and CPI. ΔSST (= estimated SST - observed SST) was predicted by the IKM (full set transfer functions) and MAT (using a Pacific data base with a cutoff value of a squared chord distance of 0.4 for the 10 most similar calibration coretops) for 132 coretops in the low-latitude Pacific at cold and warm seasons. The correlation coefficients (r) and lines in these plots were obtained from simple linear regression analyses. 17 coretops that were not considered in the residual analyses are marked with solid triangles.

Table 5. Correlation and partial correlation between the residuals of SST estimates (ΔSST = estimated SST - observed SST) and surface ocean mode 1 & 2, and carbonate preservation index (CPI).

Correlation (r)	ΔSST-IKM	ΔSST-MAT
$r_{\mathrm{Mode\ 1} \bullet \Delta SST}$	-0.38	-0.39
$r_{\mathrm{Mode\ 2} \bullet \Delta SST}$	-0.51	-0.62
$r_{\mathrm{CPI} \bullet \Delta SST}$	0.24	0.35
$r_{\mathrm{Mode\ 1} \bullet \Delta SST\ /\ \mathrm{CPI}}$#	-0.46	-0.52
$r_{\mathrm{Mode\ 2} \bullet \Delta SST\ /\ \mathrm{CPI}}$	-0.50	-0.56
$r_{\mathrm{CPI} \bullet \Delta SST\ /\ \mathrm{Mode\ 1\ \&\ 2}}$	0.01*	0.11*

* Not significant ($\alpha = 0.01$).

Partial correlation coefficients are calculated using the formula:
$r_{X \bullet (Y/Z)} = [r_{X \bullet Y} - (r_{X \bullet Z} \bullet r_{Y \bullet Z})] / \{[1 - (r_{X \bullet Z})^2] \bullet [1 - (r_{Y \bullet Z})^2]\}^{0.5}$.

variables (Chen, 1994a), were eliminated.

Simple regression analyses were performed using the remaining 115 test coretops (115 = 132 - 17) and clearly demonstrated that both the IKM and MAT predicted SST with biases toward lower estimates for coretops with positive scores of the surface ocean modes 1 and 2 and toward higher estimates for coretops with negative scores of the surface ocean modes 1 and 2 (Figure 8). Statistical tests indicated that these correlations were significant at the 99% level (Table 5) with estimated error of about 3° to 4°C. A similar regression analysis comparing SST with CPI revealed a significant though weaker relationship with biases toward lower estimates for highly dissolved coretops and higher estimates for well-preserved coretops. Because the surface ocean modes and CPI are correlated (mode 1 and CPI: +0.24; mode 2 and CPI: -0.71) in the low-latitude Pacific, their common effects on ΔSST have to be taken into account. By calculating partial correlations to remove these common influences in order to obtain adjusted estimates for the real relationships (Table 5), correlations between the ΔSST and surface ocean modes 1 and 2 were still significant and correlations between the ΔSST and CPI were no longer significant. These results suggest that (1) faunal estimates of SST are influenced by upper-layer ocean conditions which give systematic biases in the predicted SST values with errors of about 3° to 4°C; and (2) the effect of carbonate preservation on SST estimates seems to be insignificant.

This study suggests that DOT is the most important environmental variable that biases traditional IKM or MAT SST estimates in the low-latitude Pacific. To understand why estimate biases exist, we first need to consider that the DOT and SST in the low-latitude Pacific are linked through the governance of two independent modes of ocean dynamics. These two surface ocean modes, one representing a zonal and the other a meridional circulation pattern in the low-latitude Pacific, indicate that there may be a causal link between DOT and SST. Estimates of SST derived from faunal data were probably made indirectly through the more important factor DOT, and the accuracy of these estimates, to some extent, relies on the degree of correlation between DOT and SST which may vary between the two ocean modes. Therefore, different estimates of SST will be derived if the correlation between DOT and SST changes. For example, if DOT becomes shallow, low SST estimates will be given for samples from the western Pacific (mode 1 dominance area) and high SST estimates will be given for samples from the equatorial Pacific (mode 2 dominance area).

The bias patterns associated with surface ocean modes shown in Figure 8 are apparently a result of "mean condition prediction", an effect inherent in the IKM and MAT paleoestimation methods which predict the statistical average of modern surface ocean conditions based on a chosen set of coretops. In the IKM, the mean conditions of SST are determined by using regression analyses based on an ocean-wide set of calibration coretop data. In the case where faunal variations are confined within a limited SST range, scatter plot data lying above the regression line would be underestimated (negative ΔSST) and data lying below the regression line would be overestimated (positive ΔSST). This problem also exists in MAT estimates in which the mean condition of SST is obtained by taking the average of 10 or less of the most similar analogue coretop data. Biases would occur in this analysis if coretops with similar faunal compositions but different SSTs were selected. By averaging the coretop data, the IKM and MAT bias estimates toward the middle range of values, resulting in less variability in estimation values, yet losing accuracy at the high and low ends of the scale. Thus values are underestimated at the higher and overestimated at the lower extremes. This tendency was also revealed in the results from the analyses of the calibration coretop data set (Figure 6).

This examination poses questions concerning the limitations of faunal estimates of SST in the low-latitude oceans. In contrast to previous paleoceanographic studies in which the faunal composition of planktonic foraminifers is used as a proxy indicator of SST, this study indicates that in the low-latitude Pacific, DOT may be a more important indicator which can be used to interpret the ecological significance of the faunas. These results suggest that the DOT effect should be considered when estimating SST, and the CLIMAP low-latitude Pacific SST patterns during the LGM (CLIMAP, 1981) must be reevaluated. The CLIMAP estimates using planktonic foraminifers from the western tropical Pacific suggest little change (only 1° to 2°C) in SST between the LGM and the present. In contrast, continental temperature proxy records suggest that the tropics were 4° to 6°C colder then than today (Webster and Streten, 1978; Rind and Peteet, 1985). This apparent cooling of the LGM tropics has been further supported in studies using geochemical proxy indices such as Sr/Ca ratio (Beck *et al.*, 1992), noble gas thermometer (Stute *et al.*, 1992), and both oxygen isotope and Sr/Ca evidence (Guilderson *et al.*, 1994). These discrepancies suggest that the estimated CLIMAP LGM SST value for the tropics was at the low end of the scale and thus was estimated to be warmer than it should have been, by about 3° to 4°C.

These analyses have so far been limited to the environmental controls that are important to the composition of planktonic foraminifers. While it appears that the effects of upper-layer ocean conditions may account for the biases revealed in faunal estimates of SST in the low-latitude Pacific, several factors could additionally affect SST estimates. Comparisons of Pacific SST transfer functions based on different subsets of coretop data revealed discrepancies in downcore estimates (Le, 1992). Testing the accuracy of CLIMAP SST transfer functions against subsets of coretops from the other oceans also shows significant differences (Prell, 1985). These inconsistencies indicate that the accuracy of SST estimates is sensitive to the spatial distribution and range of the coretop data that are chosen for calibration. The IKM equations are derived with different sets of regression coefficients and give different estimates for identical downcore samples because the correlation between each faunal term and SST changes depending upon the subset of coretops used for calibration. The accuracy of MAT SST estimates also relies on a set of coretop data which are evenly distributed over a wide temperature range. When a more strict cutoff value for dissimilarity coefficients was used, 11 test coretops exceeded the cutoff and were not included in the analysis. The failure of the MAT in this case suggests that the coretop data currently available for the Pacific are not fully representative of all sea-surface conditions. Efforts to collect more coretop data in the Pacific will be needed in future studies.

7. CONCLUSIONS

Evaluation of faunal SST estimates using calibration and test set coretops from the low-latitude Pacific revealed biases in the statistically based estimates which are at least in part a result of changes in DOT, an environmental variable that is interrelated with both SST and faunal distribution. Coretop data sets of planktonic foraminifer faunas from modern surface sediments, seasonal observations of SST and DOT, as well as indices of carbonate preservation were compiled and analyzed in this study. A standard CLIMAP-type transfer function for estimating SST was developed and was compared to a transfer function for estimating DOT based on the same calibration coretop data set. Comparisons between these two factors demonstrated that the correlative relationship between the abundance of planktonic foraminifers and DOT was more significant, and could be applied to fossil records to accurately reconstruct DOT in paleoenvironments. In future studies, the DOT should be considered as an important indicator in interpreting the ecological significance of planktonic foraminifers in the low-latitude Pacific.

An evaluation of test set data analyzed the relationships between the residuals of SST and DOT estimates and two statistically independent low-latitude Pacific surface ocean modes as well as CPI. These residual analyses revealed that the patterns of SST estimation biases were significantly correlated with the two ocean modes through which the DOT and SST are differentially coupled. There was a bias toward predicting colder estimates for high SST values and warmer estimates for low SST values. The maximum uncertainty in these biased estimates was about 3° to 4°C. Although previous studies suggested that the change in carbonate preservation may cause biases in SST estimation, the present analysis indicates that the relationship between CPI and ΔSST was not significant and did not systematically cause estimation biases.

Paleoceanographic observations in the Pacific Ocean are complex and difficult to analyze due to limited control data, relatively low preservation of surface sediments, and complicated surface ocean dynamics. The present results indicate that with respect to the distribution and abundance of planktonic foraminifers in the low-latitude Pacific, the DOT effect may be a more important environmental control than SST. The LGM SST patterns that have been presented by the CLIMAP (1981) need to be reevaluated, taking the DOT effects into account. Furthermore, it is clear that analysis of ocean modes may be critical in future paleoceanographic applications.

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