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Recent planktonic foraminifers and their relationships to surface ocean hydrography of the South China Sea

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Abstract

The relative abundances of Recent planktonic foraminifers from surface sediments on the sea floor reveal relationships to hydrographic variables of the ocean surface. To investigate whether the effect of the vertical structure of oceanic upper-layer environments is important to the changes in the abundance of planktonic foraminifers, a set of 173 coretop faunal data from modern South China Sea (SCS) surface sediments was compiled for comparison with direct observations of sea-surface temperature (SST) and the depth of thermocline (DOT). The coretops used in this study are distributed within the area of 25°N and 105°–125°E, with water depths ranging from 68 to 3990 m. The relationships between the abundances of planktonic foraminifer species and hydrographic variables were examined using simple correlation analyses. In the analyses, four groups of planktonic foraminifers with different ecological preferences were identified: Group I – faunas primarily reliant on DOT, with positive correlations (*N. dutertrei*), Group II – faunas reliant on both SST and DOT, showing negative correlations with SST and positive correlations with DOT (*G. glutinata*, *P. obliquiloculata*, and *G. bulloides*, Group III – faunas reliant on both SST and DOT, showing positive correlations with SST and negative correlations with DOT (including *G. sacculifer*, *G. menardii*, and *G. aequilateralis*), and Group IV – faunas reliant on both SST and DOT, with positive correlations (*G. ruber*). Though each of these species displays selectivity of ecological controls, these results indicate that in the SCS, correlations between faunal abundances of planktonic foraminifers and SST or DOT are about equally significant. This study also indicates a need for re-evaluating the relationships between planktonic foraminifer abundances and many other important hydrographic variables in the upper-layer of oceans on a more regional scale. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: paleoceanography; Pacific Ocean; micropaleontology; biogeography

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1. Introduction

The recent internationally collaborated project of Past Global Changes (PAGES), organized by the IGBP (International Geosphere–Biosphere Programme), is directed at reconstructing natural- and human-induced variations in key climate systems of the past. To improve our understanding of what processes and mechanisms control variations in climate systems, paleorecords with greater resolution for as wide a geographic area as possible are required. Deciphering the data of these paleorecords into climatically interpretable signals heavily relies on the development of some useful geological proxy indices which can be used to monitor different climate system components. A classic example already demonstrated in CLIMAP projects is the development of proxy indices for planktonic microfossils that could be used to estimate past sea-surface conditions (CLIMAP, 1981).

Surface sediments contain indices of many environmental variables such as surface-, intermediate-, and deep-water conditions, as well as atmospheric and terrestrial inputs. In particular, the planktonic components of microfossil assemblages in surface sediments reveal more specific information about the modern conditions of sea-surface hydrography. Therefore, investigating correlations between surface-sediment distributions of planktonic microfossils and modern conditions of ocean hydrography can help develop useful proxy indices of microfossils for estimating past sea-surface conditions. By adopting sophisticated multivariate methods, many earlier studies have shown that a transfer function method which combines factor and regression statistical techniques is able to generate quantitative estimates of paleoenvironments (Imbrie and Kipp, 1971; Kipp, 1976). These studies based their research on distribution data of planktonic microfossils (mostly foraminifers), and include the development of paleoecological transfer functions of sea-surface temperature (SST) for the Atlantic (Kipp, 1976; Molfino et al., 1982; Pflaumann et al., 1996), the Indian (Hutson and Prell, 1980; Cullen, 1981), and the Pacific (Moore et al., 1980; Thompson, 1981; Le, 1992) oceans. This transfer function method has been extensively applied and has been used to measure

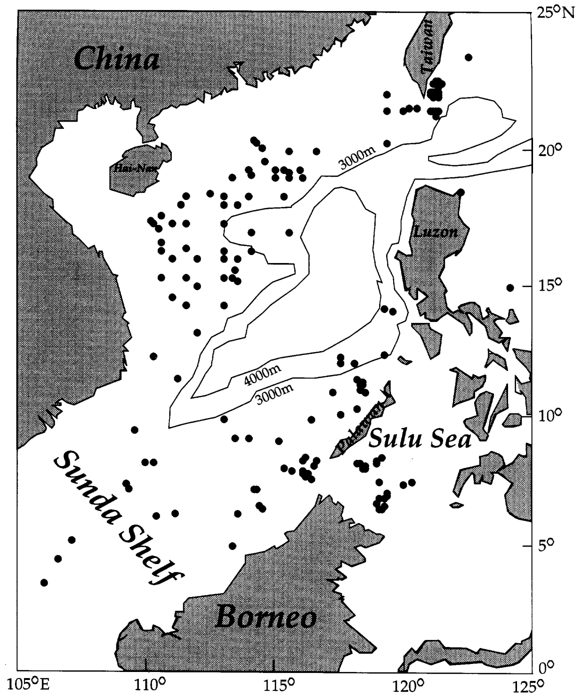

Fig. 1. Site locations of a newly compiled coretop data set ($N=173$). Bathymetric contours (3000 m and 4000 m water depths) are shown.

the relevance of many environmental variables such as SST, sea-surface salinity, and productivity.

One complication that may violate the assumption underlying the transfer function method (Imbrie and Kipp, 1971; Sachs et al., 1977; Imbrie and Webb, 1981) is that the abundance distribution of modern planktonic foraminifers seems to be jointly controlled by multiple intercorrelated environmental variables (Ravelo et al., 1990; Brock et al., 1992; Chen, 1994a). The existence of a complex structure of intercorrelated factors could lead to biased estimates for a single environmental variable when simple statistical analyses are applied for estimating the potential effects of that variable (Chen, 1994a). Previous studies have indicated that, among various environmental variables, the depth of thermocline (DOT), which reflects primarily the stratification conditions of oceanic upper-layers, seems to be an important control in the distribution patterns and abundances of planktonic foraminifers in the Atlantic (Ravelo

Table 1
Sources of the South China Sea (SCS) planktonic foraminifer coretop data bases

Authors	Number of coretops
Shieh and Chen (1984)	18
Rottman (1979)	31
Wang et al. (1992)	6
Miao et al. (1994)	36
Chen and Kuo (1986)	3
Yin (1991)	9
Huang (1990)	22
Ho et al. (1997)	48
Total	173

et al., 1990), the Indian (Brock et al., 1992), and the Pacific (Chen, 1994b) oceans, and also in the Mediterranean Sea (Pujol and Vergnaud Grazzini, 1995).

The South China Sea (SCS) is located in the western equatorial Pacific and is a semi-enclosed deep ocean basin in which calcareous sediments are well preserved on the sea floor. Though the SCS is influenced by the proximity of adjacent Asian continents, the sediments deposited resemble those of the open oceans. Consisting mostly of a biogenic fraction derived from organisms that once had lived as plankton in the surface water, and a terrigenous component derived from the neighboring continents, the SCS sediments show typical characteristics of very high sedimentation rates which allow us to use the sediments for high-resolution paleoclimatic studies. Earlier studies of surface-sediment distributions of planktonic foraminifers in the SCS have accumulated adequate samples with a wide geographic coverage, but we still have little knowledge about the relationships between the distributions of faunas and of sea-surface hydrographic conditions. In this study, we compiled and analyzed data on 173 planktonic foraminifer faunal abundances that were previously collected from the SCS (Fig. 1). The objectives of this research were (1) to document the seasonal patterns of the environmental variables SST and DOT in the SCS and their relationships with faunal abundance distributions; (2) to compare the relative correlations between seasonal SST and DOT and some important species abundance

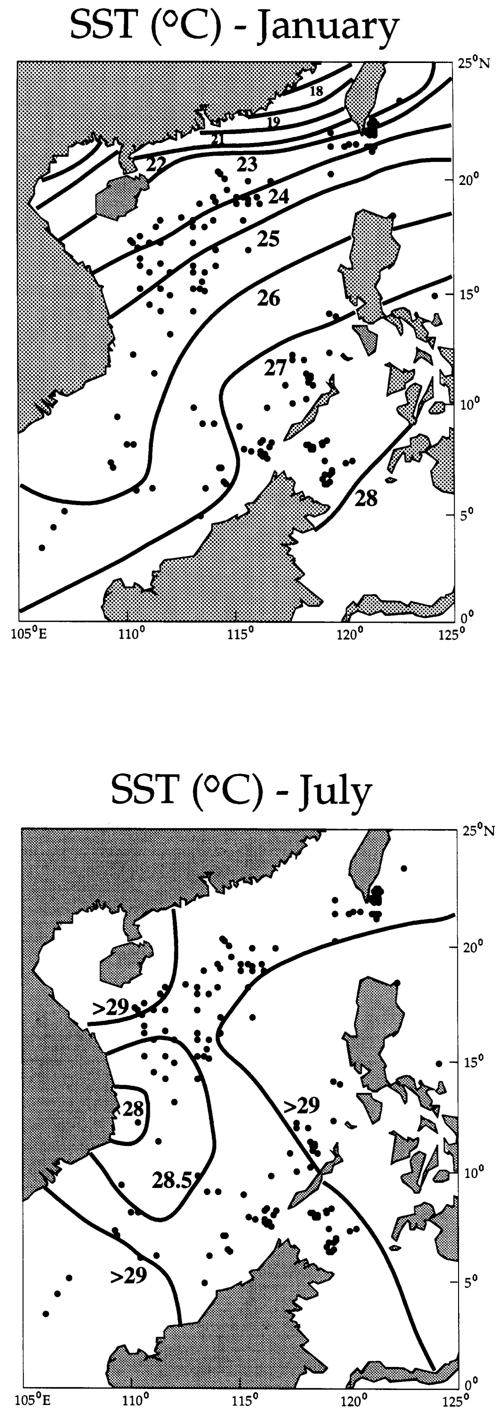

Fig. 2. Monthly mean SST of January and July in the SCS. Contoured using 1° × 1° digital data from Levitus (1982, 1987). Site locations of 173 coretops are shown by small dots.

Table 2
Identifications, locations, depths, observed sea-surface temperatures (SST) and the depth of thermocline (DOT), and dissolution-resistant species percentage (RSP) of 173 coretops from the South China Sea

Core ID	Latitude	Longitude	Depth	SST		DOT		RSP
			(m)	January	July	January	July	(%)
V19-137	5.24	107.11	68	25.70	29.08	–	–	10.7
V19-138	4.56	106.55	77	25.95	29.16	–	–	8.4
V19-139	3.58	106.02	81	26.17	29.21	–	–	8.0
C14-86	16.03	113.54	338	24.97	28.98	127.2	130.7	17.5
C14-81	11.00	117.24	342	27.23	29.05	139.3	136.3	29.5
C12-353	7.27	114.33	706	26.96	28.82	165.0	135.3	48.7
C14-79	8.54	116.18	525	27.24	29.13	153.4	135.1	19.8
V19-134	8.27	110.00	1031	26.10	28.48	143.8	139.3	26.8
C12-354	7.30	114.13	1161	26.96	28.82	165.0	135.3	28.5
C12-351	5.02	113.35	1229	26.73	28.65	–	–	20.5
C12-355	7.30	114.30	1341	26.96	28.82	165.0	135.3	57.9
C12-356	7.30	114.13	1344	26.96	28.82	165.0	135.3	14.9
C17-146	6.21	110.33	1390	26.00	28.90	157.3	145.8	26.0
C14-80	10.01	116.35	1743	27.28	29.01	139.7	132.7	26.1
V24-134	8.50	119.14	2019	27.68	29.05	146.6	144.6	24.0
C14-82	11.34	118.30	2275	27.27	29.07	143.2	138.5	51.0
C14-85	15.25	113.49	2470	25.45	28.93	124.3	132.9	16.3
V19-119	14.15	119.23	2573	26.66	29.21	137.8	153.3	57.2
RC12-350TW	6.33	111.13	1950	26.28	28.85	159.4	143.6	23.9
ANT-176	6.35	113.51	2440	26.75	28.71	164.2	140.4	22.2
LSDA-2G	6.48	114.44	2886	26.83	28.69	176.1	138.8	33.0
ANT-178	6.58	114.40	2882	26.83	28.69	176.1	138.8	30.6
TSDY-12G	7.30	109.30	850	25.76	28.71	151.1	146.0	24.1
CIR-18	7.55	119.03	200	27.82	29.03	148.1	149.2	23.5
SCS-3	8.14	115.37	2818	27.16	28.99	154.4	132.6	40.4
LSDA-3G	8.14	115.37	2818	27.16	28.99	154.4	132.6	32.3
AH-8	8.22	116.49	201	27.24	29.13	153.4	135.1	16.7
TSDY-10G	8.30	110.30	1454	26.10	28.48	143.8	139.3	27.5
CIR-19	8.30	118.33	1781	27.57	29.09	146.6	142.3	25.3
SCS-4A	8.37	116.03	2280	27.24	29.13	153.4	135.1	21.2
AH-7	8.45	116.57	914	27.24	29.13	153.4	135.1	16.2
RC14-79TW	8.53	116.18	706	27.24	29.13	153.4	135.1	25.7
LSDA-6G	9.11	115.08	2360	27.22	28.96	144.0	131.6	36.7
LSDA-8G	9.20	114.01	2700	27.12	28.83	141.6	132.8	67.0
LSDA-9G	9.29	113.44	2444	26.98	28.69	138.8	134.9	43.6
LSDA-13G	9.56	109.50	494	25.72	27.95	132.2	133.7	16.8
SCS-11	10.00	113.02	2090	26.95	28.64	131.2	134.7	42.3
AH-5	10.20	117.58	1152	27.35	29.06	141.9	134.6	16.4
AH-4	11.12	118.30	1170	27.27	29.07	143.2	138.5	13.5
RC0-113	11.55	111.23	3100	26.32	28.07	130.0	132.1	33.0
TSDY-11G	12.30	110.30	414	25.59	27.75	139.7	122.0	17.0
AH-1	12.50	119.21	2030	27.09	29.14	149.5	144.8	27.5
V24-126	14.14	119.50	2518	26.66	29.21	137.8	153.3	55.7
RC12-361	15.06	124.08	3528	27.14	29.61	201.8	224.5	36.8
RC0-121	18.30	115.30	3810	24.22	28.96	130.5	127.8	69.8
V21-133	18.57	122.23	1928	25.74	29.67	205.2	220.0	7.3
RC0-117	20.30	119.30	3350	24.25	28.85	156.4	161.4	36.8
V28-313	23.45	122.49	3298	23.37	28.83	227.5	230.3	23.9
V28-311	25.31	122.53	1140	22.53	28.76	214.4	213.8	23.6
GGC4	12.39	117.56	3530	27.05	29.06	136.1	139.3	54.0

Table 2 (*continued*)
Identifications, locations, depths, observed sea-surface temperatures (SST) and the depth of thermocline (DOT), and dissolution-resistant species percentage (RSP) of 173 coretops from the South China Sea

Core ID	Latitude	Longitude	Depth	SST		DOT		RSP
			(m)	January	July	January	July	(%)
GGC5	12.19	117.55	3185	27.05	29.06	136.1	139.3	66.3
GGC6	12.09	118.04	2975	27.10	29.09	141.5	141.9	63.5
GGC7	10.99	118.48	990	27.40	29.07	144.1	136.9	15.0
GGC8	11.35	118.43	1305	27.27	29.07	143.2	138.5	12.8
GGC9	11.38	118.38	1465	27.27	29.07	143.2	138.5	19.5
GGC10	11.43	118.31	1605	27.27	29.07	143.2	138.5	22.5
GGC11	11.53	118.20	2165	27.27	29.07	143.2	138.5	28.9
GGC12	11.56	118.13	2495	27.27	29.07	143.2	138.5	32.3
GGC13	10.36	118.17	990	27.40	29.07	144.1	136.9	13.8
GGC14	7.70	116.41	825	26.97	29.30	164.3	139.9	20.0
GGC15	7.84	116.23	1740	26.97	29.30	164.3	139.9	21.0
GGC16	7.98	116.05	2820	26.97	29.30	164.3	139.9	25.0
GGC17	8.00	115.65	2920	27.16	28.99	154.4	132.6	26.9
GGC18	7.88	116.12	2295	26.97	29.30	164.3	139.9	22.5
GGC19	7.82	116.17	1835	26.97	29.30	164.3	139.9	19.1
GGC21	8.10	118.46	695	27.57	29.09	146.6	142.3	22.4
GGC22	8.10	118.50	845	27.57	29.09	146.6	142.3	22.3
GGC23	8.09	118.34	990	27.57	29.09	146.6	142.3	25.6
GGC24	8.13	118.43	1380	27.57	29.09	146.6	142.3	26.5
GGC25	8.18	118.54	1750	27.57	29.09	146.6	142.3	25.9
GGC26	8.36	118.96	1965	27.57	29.09	146.6	142.3	22.6
GGC27	8.30	118.15	2030	27.57	29.09	146.6	142.3	24.2
GGC28	8.32	118.93	1825	27.57	29.09	146.6	142.3	23.8
GGC29	8.18	118.50	1535	27.57	29.09	146.6	142.3	25.6
GGC30	8.11	118.38	1170	27.57	29.09	146.6	142.3	17.9
GGC31	6.74	118.88	2295	27.59	29.02	150.7	159.9	27.5
GGC33	6.50	119.02	2705	27.95	28.98	150.9	156.2	23.4
GGC34	6.54	119.10	2970	27.95	28.98	150.9	156.2	23.8
GGC35	6.59	119.22	3250	27.95	28.98	150.9	156.2	20.9
GGC36	7.54	120.33	3990	27.93	29.03	149.6	153.0	58.2
GGC40	7.49	119.93	3800	27.82	29.03	148.1	149.2	36.5
GGC41	7.13	119.32	3590	27.82	29.03	148.1	149.2	21.2
GGC42	7.10	119.29	3430	27.82	29.03	148.1	149.2	23.2
GGC43	6.97	119.25	3120	27.82	29.03	148.1	149.2	22.1
GGC44	6.89	119.06	2850	27.82	29.03	148.1	149.2	25.5
RC14-085	15.25	113.49	2470	25.45	28.93	124.3	132.9	16.1
RC12-350	6.33	111.13	1950	26.28	28.85	159.4	143.6	13.0
V36-003	19.01	116.06	2809	23.80	28.87	133.6	128.3	36.6
V36-005	19.26	115.55	2332	23.54	28.87	138.0	124.8	19.0
SO49-8KL	19.11	114.12	1040	23.38	28.85	140.4	126.7	24.3
SCS-12	7.42	109.18	543	25.76	28.71	151.1	146.0	21.7
KS-11	21.50	120.00	1700	24.01	28.97	188.2	189.5	59.7
TS-9	22.15	119.30	1630	21.93	28.70	179.8	168.1	30.2
TS-11	21.55	119.30	2290	23.34	28.74	171.6	166.1	31.2
203-02B	22.08	121.06	1290	23.77	29.06	213.6	219.7	30.4
203-03B	22.08	121.08	1292	23.77	29.06	213.6	219.7	30.4
203-08B	21.30	121.29	2213	24.44	28.96	200.9	209.1	19.5
203-09B	21.31	121.22	2682	24.44	28.96	200.9	209.1	16.4
203-11B	22.02	121.36	364	23.77	29.06	213.6	219.7	48.2
203-12B	21.59	120.21	1421	24.01	28.97	188.2	189.5	39.1

Table 2 (*continued*)
Identifications, locations, depths, observed sea-surface temperatures (SST) and the depth of thermocline (DOT), and dissolution-resistant species percentage (RSP) of 173 coretops from the South China Sea

Core ID	Latitude	Longitude	Depth	SST		DOT		RSP
			(m)	January	July	January	July	(%)
227-02B	22.51	121.20	662	23.77	29.06	213.6	219.7	43.3
227-07B	22.59	121.25	168	23.77	29.06	213.6	219.7	43.6
CI-16	22.55	121.32	1825	23.77	29.06	213.6	219.7	23.4
OR102-3	22.19	121.17	1309	23.77	29.06	213.6	219.7	30.9
OR102-6	22.17	121.29	495	23.77	29.06	213.6	219.7	25.5
OR102-7	21.50	121.16	815	24.44	28.96	200.9	209.1	46.7
OR151-6	22.45	121.30	1046	23.77	29.06	213.6	219.7	35.3
OR170-2	22.07	121.00	1260	23.77	29.06	213.6	219.7	10.5
OR170-6	22.05	121.09	1290	23.77	29.06	213.6	219.7	20.8
OR170-7	22.06	121.15	1500	23.77	29.06	213.6	219.7	22.9
OR170-20	21.55	121.33	1200	24.44	28.96	200.9	209.1	40.0
OR182-3B	21.59	120.55	373	24.01	28.97	188.2	189.5	30.9
OR215-4B	22.59	121.29	2047	23.77	29.06	213.6	219.7	43.5
OR216-1B	21.50	121.02	1310	24.44	28.96	200.9	209.1	45.5
OR216-2B	21.50	121.11	1101	24.44	28.96	200.9	209.1	48.7
OR216-3B	21.50	121.21	2850	24.44	28.96	200.9	209.1	12.5
OR216-13B	22.13	121.30	900	23.77	29.06	213.6	219.7	43.3
OR216-14B	22.20	121.12	885	23.77	29.06	213.6	219.7	18.8
OR216-17B	22.43	121.30	757	23.77	29.06	213.6	219.7	23.4
OR219-1B	22.50	121.17	815	23.77	29.06	213.6	219.7	27.3
OR219-2B	22.50	121.19	715	23.77	29.06	213.6	219.7	29.7
OR219-4B	22.55	121.31	1795	23.77	29.06	213.6	219.7	22.9
OR219-5B	22.48	121.40	2900	23.77	29.06	213.6	219.7	34.2
OR219-10B	22.17	121.30	370	23.77	29.06	213.6	219.7	24.0
OR219-12B	22.21	121.08	1128	23.77	29.06	213.6	219.7	20.2
G-22	14.31	111.59	1699	25.42	28.51	131.3	123.8	56.1
G-23	14.30	113.00	2398	25.89	28.84	123.0	134.4	52.8
G-29	15.30	110.59	900	24.73	28.61	140.2	115.3	17.2
G-30	15.31	111.59	1579	25.04	28.72	132.3	122.3	24.3
G-31	15.30	113.00	2800	25.45	28.93	124.3	132.9	67.6
G-32	15.30	113.30	2600	25.45	28.93	124.3	132.9	17.6
G-37	16.02	111.00	384	24.62	28.88	134.5	121.4	30.2
G-38	16.00	112.00	1115	24.81	28.93	130.2	126.5	19.0
G-39	16.01	113.01	1747	24.97	28.98	127.2	130.7	18.6
G-40	15.60	113.45	2420	25.45	28.93	124.3	132.9	10.8
G-45	17.16	110.50	1600	23.99	29.05	141.3	118.8	28.9
G-46	16.60	110.59	1310	24.38	28.86	140.8	116.3	24.1
G-47	17.00	115.59	981	24.79	29.04	125.5	131.1	16.3
G-49	17.02	114.03	2850	24.61	29.01	128.9	129.9	53.1
G-54	17.30	110.31	1230	23.99	29.05	141.3	118.8	23.2
G-55	17.30	111.00	1760	24.20	28.96	137.0	120.1	40.3
G-56	17.31	111.59	1347	24.20	28.96	137.0	120.1	23.2
G-57	17.31	113.00	1432	24.46	28.97	131.4	128.0	27.0
G-63	18.30	111.59	480	23.77	28.89	138.9	115.5	15.5
G-64	18.45	112.46	600	23.87	28.87	136.8	121.8	17.2
G-65	18.30	113.00	1659	23.93	28.90	136.0	126.3	34.7
G-66	18.30	114.00	2172	24.04	28.94	133.9	127.2	18.6
G-71	19.00	113.30	1040	23.36	28.78	140.9	127.9	17.7
G-72	19.00	115.00	2234	23.54	28.87	138.0	124.8	55.4
G-73	19.00	115.59	2970	23.54	28.87	138.0	124.8	70.2

Table 2 (*continued*)
Identifications, locations, depths, observed sea-surface temperatures (SST) and the depth of thermocline (DOT), and dissolution-resistant species percentage (RSP) of 173 coretops from the South China Sea

Core ID	Latitude	Longitude	Depth	SST		DOT		RSP
			(m)	January	July	January	July	(%)
G-76	19.29	115.29	2400	23.54	28.87	138.0	124.8	61.3
G-77	19.60	114.59	895	23.38	28.85	140.4	126.7	20.9
G-78	20.00	115.59	1257	22.67	28.84	150.4	122.4	26.2
G-79	20.00	116.59	1822	22.92	28.78	142.0	130.6	16.8
G-82	17.44	110.15	160	23.99	29.05	141.3	118.8	16.9
G-87	20.45	114.16	84	22.54	28.82	147.2	129.5	26.4
G-88	20.30	114.30	104	22.54	28.82	147.2	129.5	23.0
G-89	20.15	114.44	181	22.54	28.82	147.2	129.5	20.6
8311	19.30	114.00	560	23.38	28.85	140.4	126.7	20.5
8312	19.30	115.00	1640	23.54	28.87	138.0	124.8	23.1
8313	19.30	116.00	1937	23.80	28.87	133.6	128.3	22.6
8321	17.60	110.59	1200	23.99	29.05	141.3	118.8	15.4
8322	18.00	113.59	2412	23.93	28.90	136.0	126.3	29.1
S-8322	18.00	111.35	2085	23.77	28.89	138.9	115.5	17.0
8323	18.01	113.00	2050	23.93	28.90	136.0	126.3	32.1
8324	18.00	113.59	3242	23.93	28.90	136.0	126.3	77.0
8331	16.30	110.59	1163	24.38	28.86	140.8	116.3	15.6
8332	16.40	111.59	910	24.62	28.88	134.5	121.4	17.0
8333	16.30	113.00	1244	24.97	28.98	127.2	130.7	17.3
8334	16.35	114.03	3200	25.12	29.03	125.0	133.0	66.4
8341	14.60	111.00	1240	25.42	28.51	131.3	123.8	32.5
8342	15.01	112.00	1670	25.27	28.83	127.0	128.6	28.0
8351	13.30	112.00	2300	26.07	28.55	124.6	131.7	31.1

data; and (3) to improve our understanding of how significant variations in SST and DOT can control the faunal abundance distribution in the SCS area.

2. Hydrographic setting

The SCS is a region under strong influence by the east Asian monsoon system (Wyrtki, 1961). Surface water circulation is mainly driven by the annually reversing monsoon winds. During the northeast winter monsoon season (November–April), cold Chinese coastal waters from the Yellow and East China Seas flow into the SCS through the Taiwan Strait (Niino and Emery, 1961). During the same season, warm Kuroshio Currents bring warm surface waters into the SCS through the Luzon Strait (Samodai et al., 1986). The convergence of these two surface water masses in the SCS results in a large north–south SST gradient, with a range from 18°C in the north to 27°C in the south (Fig. 2).

During the southwest monsoon season (May–October), warm equatorial surface waters flow northeastward over the shallow Sunda and Borneo shelves into the SCS. At the same time another branch of equatorial surface waters enters the Sulu Sea through the Mindanao Strait. Associated with this pattern of circulation, the distribution of summer SST in the SCS is quite uniform, ranging from approximately 28 to 29°C (Fig. 2).

3. Data and methods

The set of 173 coretop data used in this study was collected from various sources of published counts generated by different authors (Rottman, 1979; Shieh and Chen, 1984; Chen and Kuo, 1986; Huang, 1990; Yin, 1991; Wang et al., 1992; Miao et al., 1994; Ho et al., 1997; Tables 1 and 2). The

Table 3
Comparison of descriptive statistics for 27 planktonic foraminifer species percentages, resistant species percentage (RSP), core depth, and observed seasonal SST and DOT from 173 coretops in the South China Sea

Foraminifer species	Average (%)	Std. Dev. (%)	Range (%)	Minimum (%)	Maximum (%)
Orbulina universa	0.8	0.9	7.0	0.0	7.0
Globigerinoides conglobatus	1.0	1.8	21.1	0.0	21.1
Globigerinoides ruber	22.0	9.8	52.8	1.4	54.2
Globigerinoides tenellus	1.3	1.4	6.0	0.0	6.0
Globigerinoides sacculifer	14.7	6.6	41.0	0.0	41.0
Sphaeroidinella dehiscens	0.7	2.1	21.1	0.0	21.1
Globigerinella aequilateralis	3.5	2.6	12.2	0.0	12.2
Globigerina calida	2.9	2.7	16.2	0.0	16.2
Globigerina bulloides	7.2	4.8	36.3	0.0	36.3
Globigerina falconensis	0.6	0.7	3.6	0.0	3.6
Globigerina digitata	0.4	0.9	9.0	0.0	9.0
Globigerina rubescens	1.3	1.3	6.3	0.0	6.3
Globigerina pachyderma L.	0.0	0.1	1.8	0.0	1.8
Globigerina pachyderma R.	0.1	0.4	4.3	0.0	4.3
Neogloboquadrina dutertrei	11.6	6.2	44.4	2.8	47.2
Globoquadrina conglomerata	0.3	0.6	3.1	0.0	3.1
Globoquadrina hexagona	0.2	0.6	4.8	0.0	4.8
Pulleniatina obliquiloculata	8.6	5.5	31.4	1.3	32.7
Globorotalia inflata	0.3	1.2	11.1	0.0	11.1
Globorotalia truncatulinoides L.	0.0	0.0	0.1	0.0	0.1
Globorotalia truncatulinoides R.	0.3	0.5	2.6	0.0	2.6
Globorotalia crassaformis	0.2	0.5	3.6	0.0	3.6
Globorotalia hirsuta	0.0	0.1	0.6	0.0	0.6
Globorotalia scitula	0.5	0.6	2.7	0.0	2.7
Globorotalia menardii	6.8	7.8	40.4	0.0	40.4
Globorotalia tumida	0.5	1.5	13.0	0.0	13.0
Globigerinita glutinata	14.4	8.5	38.5	0.8	39.3
RSP (%)	29.2	14.4	69.7	7.3	77.0
Core depth (m)	1689.9	941.4	3922.0	68.0	3990.0
SST January (°C)	25.5	1.7	6.1	21.9	28.0
SST July (°C)	29.0	0.2	1.9	27.8	29.7
DOT January (m)	157.7	28.9	104.5	123.0	227.5
DOT July (m)	152.3	34.5	114.9	115.4	230.3

coretop samples studied by Shieh and Chen (1984) and compiled by Rottman (1979) were piston cores collected by the Lamont–Doherty Geological Observatory R/V *Vema* and *Conrad* during 1963–1970. Coretop samples used in Wang et al. (1992) were also piston cores collected from cruises of the R/V *Vema*, with some from that of the *Sonne* of Germany in 1987. Coretops provided by Miao et al. (1994) are giant gravity cores drilled from the very southeastern part of the SCS and from the Sulu Sea in 1988. We also added coretop data generated from local piston or box core studies, primarily in the southern Taiwan strait area (Chen and Kuo, 1986; Huang, 1990; Yin, 1991). A recently-generated data set of 48 coretops (Ho et al., 1997), which are mostly from the northern part of the SCS, are based on grab samples provided by the Second Institute of Oceanography, SOA, Hangzhou, P.R.C.

The geographic range of the whole 173 coretop data is from a latitude of 0° to 25°N and a longitude of 105° to 125°E (Fig. 1). According to the sample processing procedures described in these studies, all samples used to generate faunal counting data were weighed and sieved through a 150 μm sieve. Census counts of planktonic foraminifers were made on fractions ≥150 μm and at least 300 whole specimens were counted for each sample.

The relative abundance of each faunal species is expressed as the percentage of the total faunal assemblages that were counted. Descriptive statistics of the relative abundances of 27 species of planktonic foraminifers were calculated for the data set (Table 3). The taxonomy of planktonic foraminifers used in this study is based on Parker (1962), Bé (1967) and Kipp (1976), and was also used in previous studies of late Quaternary equatorial Indo-Pacific foraminifers (Chen, 1994a). This analysis (Table 3) shows that the foraminifer assemblage of this data set is dominated by eight species which constitute about 89% of the total planktonic foraminifer composition. In order of decreasing mean abundance, the eight species are: *Globigerinoides ruber* (Fig. 3.1a), *Globigerinoides sacculifer* (Fig. 3.1b), *Globigerinita glutinata* (Fig. 3.1c), *Neogloboquadrina dutertrei* (Fig. 3.1d), *Pulleniatina obliquiloculata* (Fig. 3.2a), *Globigerina bulloides* (Fig. 3.2b), *Globorotalia menardii* (Fig. 3.2c), and *Globigerinella aequilateralis* (Fig. 3.2d). These eight species showed greater variation than the less abundant species, as revealed by their larger standard deviations.

These coretop samples ranged in water depth from 68 m to 3990 m, a wide interval that overlaps the depth of the regional lysocline (~2200–3000 m; Rottman, 1979; Shieh and Chen, 1984). The ratio of dissolution-resistant species (RSP), calculated according to the methods by Cullen and Prell (1984), ranged from 7.3% to 77.0%, indicating that the samples were deposited under various carbonate preservation conditions. The index of RSP has been used to evaluate the status of carbonate dissolution and preservation (Cullen and Prell, 1984). The presence of high abundances of carbonate dissolution-resistant species (high RSP) in samples from deeper depths indicates that these species may have experienced stronger dissolution conditions.

SST observation values for each of the 173 coretop sites were determined from a NOAA compilation for January and July climatologies (Levitus, 1982, 1987). DOT was also calculated for each coretop site using the NOAA's subsurface temperature data for examining the thermal structure of upper-layer oceans. The DOT was estimated by the depth of the 18°C isotherm, which corresponds to the depth displaying the most dramatic change in temperature in the tropical oceans. This computation of the DOT has been recently applied in monitoring the surface circulation of the tropical Atlantic (Houghton, 1991) and tropical Pacific (McPhaden and Hayes, 1991; Hayes et al., 1991) Oceans. DOT January and DOT July were defined on the basis that the seasons were determined by SST. Statistical analyses (Table 3) revealed that, over the range of coretop distribution, SST January data were characterized by larger spatial variations than were SST July data (Fig. 2). In contrast, spatial variations between DOT January and DOT July data were approximately the same, with a range of only about 100 m (Fig. 4).

To compile a manageable coretop data set and fulfil the objectives presented above, this study was designed to fulfil the three aims listed below.

(1) To compile a set of newly collected coretop data from the surface sediments of the SCS which contain hydrographic data of DOT and SST from two seasons, represented by January and July, as well as abundance data of planktonic foraminifer fauna.

(2) To use an index of RSP and water depths and to identify carbonate preservation conditions of coretop samples, and in order to minimize the effect of dissolution, classify the data set into three subsets of high-, medium-, or low- carbonate preservation status.

(3) To analyze statistically the correlation between the environmental variables, DOT and SST, and eight dominant planktonic foraminifer species for each preservation subset, as well as to compare and discuss the relative importance of using DOT and/or SST in future paleoestimation studies.

4. Statistical analysis

4.1. Coretop examination

Reconstructions of past SST based on marine microfossils require using a set of coretops that

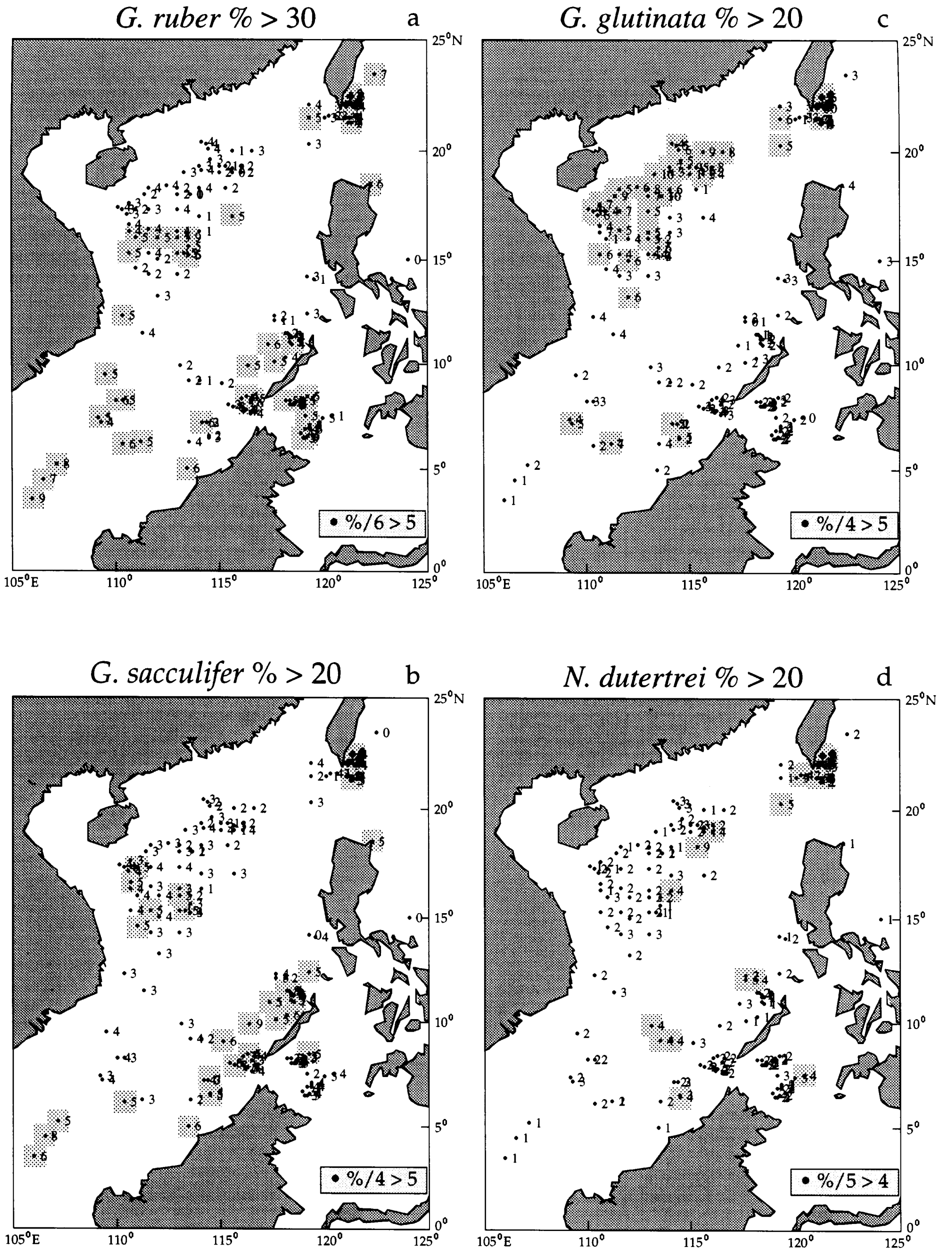

Fig. 3. Distributions of the abundances of eight dominant planktonic foraminifer species in the SCS (data from a data set of 173 coretops). High abundances are shown by shaded area (numbers associated with each core location '●' are adjusted species abundances; for example, the abundances of *G. ruber* (≥30% in 1a) have been divided by 6 and represented by shading for values greater than 5.

are the most recently deposited sediments. Contamination with exotic or non-Recent faunas might lead to significant, yet undetectable biases in paleoestimation. A recent study of downward fluxes of particulate matter in the SCS using time-series sediment traps (Wiesner et al., 1996) has

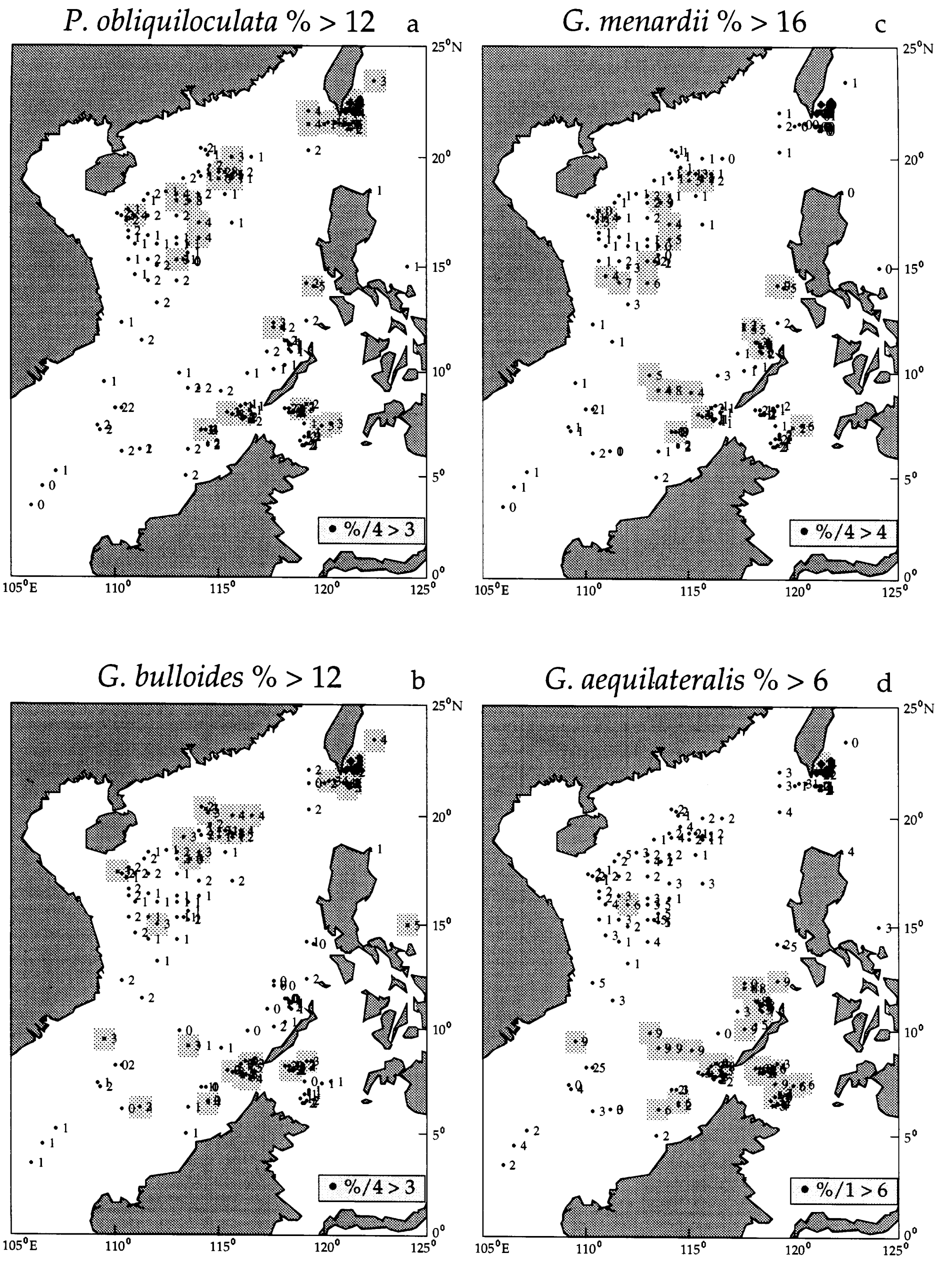

Fig. 3. (*continued*)

documented a rapid down-column transfer and ruled out horizontal advection of particles or faunas. Moreover, while information on direct age-controls for the coretop data set used in this study is lacking, we used indirect criteria for judging whether the coretops were modern sediments or not. Water depth variations in preservation indices from the SCS coretops show a distinct change in preservation at the depth of lysocline (Fig. 5), which can be used to compare to the

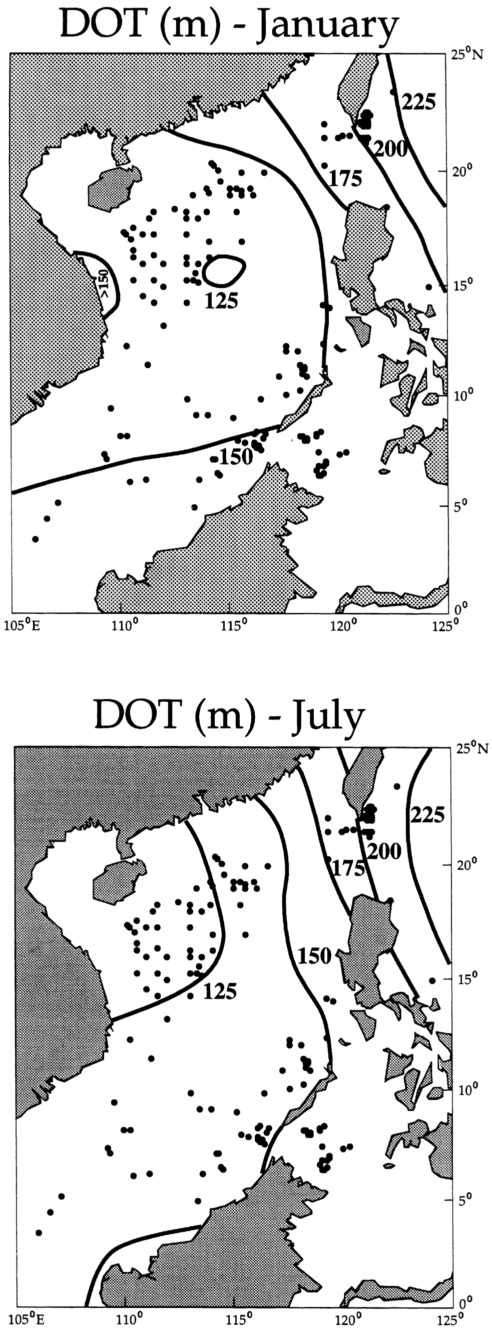

Fig. 4. Monthly mean DOT of January and July in the SCS. The depth of thermocline is estimated by the depth of the 18°C isotherm using the temperature-depth data (1°×1°) from Levitus (Levitus, 1982, 1987). Site locations of 173 coretops are shown by small dots.

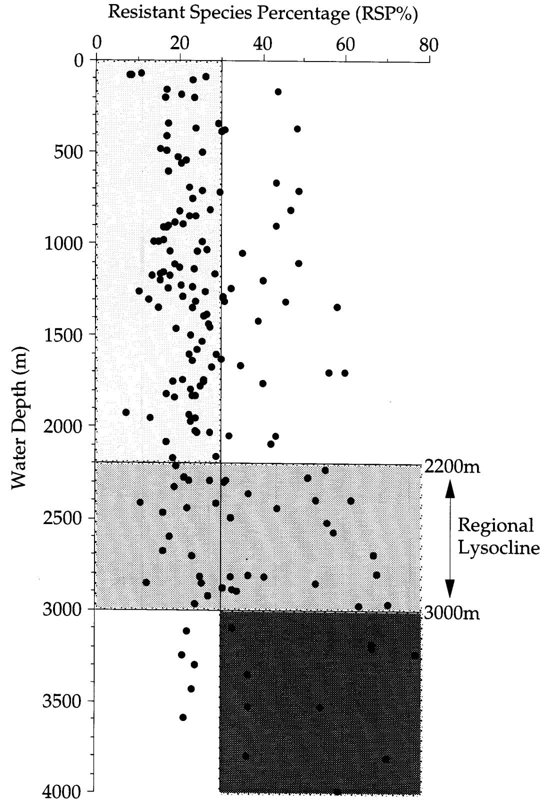

Fig. 5. Bathymetric profile of the RSP for the 92 South China Sea coretops (RSP = abundance of dissolution-resistant species as defined by Cullen and Prell, 1984). The index of RSP was used to measure the preservation level of coretop samples. 30% RSP approximately corresponds to the position of the foraminiferal lysocline (*FL*; Cullen and Prell, 1984). A wide interval of depths from 2200 m to 3000 m overlaps the depth of regional lysocline reported previously based on other evidence (Shieh and Chen, 1984; Rottman, 1979).

depth of the regional lysocline reported previously (2200–3000 ml; Rottman, 1979; Shieh and Chen, 1984). One coretop study in the tropical Indian Ocean (Cullen and Prell, 1984) indicated that the position of the lysocline corresponded to an RSP value of approximately 30. Evaluating preservation indices for the 173 coretops collected here based on these criteria, we identified 31 coretops which were characterized by deviant RSP values (Fig. 5). Five coretop samples were poorly preserved (>30 RSP%) but were found above the depth of the reported lysocline (depth <2200 m) and 26 coretop samples were well preserved (<30 RSP%) but were found below the depth (depth >3000 m; Fig. 5). Sediments that are poorly preserved but are found above the lysocline may have resulted from an anomalous calcium carbonate saturation state or from increased winnowing caused by vigorous local bottom currents; and sediments that are well preserved but are found below the lysocline are suspected to be either non-Recent samples, because Pacific and SCS glacial sediments are characterized by good preservation (Farrell and Prell, 1989; Chen et al., 1997). In addition to these factors, local productivity variations may also play a role in shaping the RSP–depth relationship. The lysocline fluctuation in the SCS may either reflect a change in the state of CO_3^{2-} saturation of Pacific deep waters, and may also be caused by a change of $CaCO_3$ productivity and/or of organic (siliceous) productivity in SCS surface waters. An early study of SCS surface sediments (Rottman, 1979) has indicated that there are two levels of rapid increases in carbonate dissolution at 2000 m and 3200 m, suggesting a complex preservation pattern. In all, the deviant RSP values of the 31 coretops identified here (Fig. 5) maybe resulted from post-depositional alteration and erosion or, most likely from the real ocean processes that govern the preservation pattern of SCS surface sediments. Thus, we keep all coretop data in the subsequent analyses. We emphasize that the reservation of the 31 coretop data did not affect the conclusions of this study, and when comparing the results of these analyses with the 31 coretops either included or excluded, we found only minor discrepancies.

4.2. Correlation analyses

Before examining how variations in SST and DOT correlate the faunal abundance distributions of planktonic foraminifers in the SCS area, we calculated first the correlation between the bathymetric changes in carbonate preservation and the abundances of eight important faunal species from a total of 173 coretop data (Table 4). The calculation shows that the abundances of *G. ruber* and *G. menardii* are significantly-correlated with water depths. *G. ruber* is a dissolution-susceptible species. The negative correlation ($r = -0.42$) indicates that the species abundance decreases in deep water depth. *G. menardii* is a dissolution-resistant species. Increases in the species abundances in deep water depth are reasonably revealed by the positive correlation ($r = 0.40$). This result suggests the presence of a preservation control to faunal distributions in the SCS.

Table 4
Correlation between eight important planktonic foraminifer species percentage data and water depth and resistant species percentage (RSP) of 173 South China Sea coretops

	Water depth
Globigerinoides ruber	−0.42
Globigerinoides sacculifer	−0.14
Globigerinita glutinata	−0.03
Neogloboquadrina dutertrei	0.13
Pulleniatina obliquiloculata	0.16
Globigerina bulloides	−0.14
Globorotalia menardii	0.40
Globigerinella aequilateralis	0.06

The correlation matrices (Table 5) revealed meaningful relationships between the seasonal DOT and/or SST and the abundances of eight planktonic foraminifer species. The 173 coretop data were classified into three subsets for the analyses: high-preservation (0–2200 m), medium-preservation (2200–3000 m), and low-preservation (>3000 m). This division may minimize the various effects of carbonate dissolution over different depths when identifying the real relationships between other environmental variables (DOT and SST) and faunal abundances.

Within these three subsets, we found that many faunal species were significantly correlated with DOT and/or SST (Table 5). The results revealed that the abundances of *G. glutinata*, *P. obliquiloculata*, and *G. bulloides* had a significant negative correlation with SST; whereas the abundances of *G. ruber*, *G. sacculifer*, *G. menardii* and of *G. aequilateralis* showed a positive correlation with SST. Moreover, *G. sacculifer*, *G. menardii*, as well as *G. aequilateralis*, were negatively correlated with DOT, while *G. ruber*, *G. glutinata*, *N. dutertrei*, *P. obliquiloculata*, and *G. bulloides* exhibited a positive correlation with DOT (Table 5).

These complex correlations indicate that both of these hydrographic variables seem to be impor-

Table 5
Correlation between eight important planktonic foraminifer species percentage data and seasonal SST and DOT data of 173 South China Sea coretops

	SST January			SST July		
	H ($N=118$)	M ($N=40$)	L ($N=15$)	H ($N=118$)	M ($N=40$)	L ($N=15$)
Globigerinoides ruber	**0.36**	0.15	0.19	0.01	0.06	−0.32
Globigerinoides sacculifer	**0.42**	**0.39**	**0.68**	0.15	0.23	−0.22
Globigerinita glutinata	−**0.52**	−**0.60**	−**0.45**	−0.17	−0.18	−0.36
Neogloboquadrina dutertrei	−0.25	0.18	−0.35	−0.04	−0.23	−0.13
Pulleniatina obliquiloculata	−**0.34**	−**0.42**	−0.41	0.09	−0.05	−0.10
Globigerina bulloides	−**0.42**	−0.21	−0.24	0.01	−0.16	0.21
Globorotalia menardii	**0.34**	0.12	−0.18	−0.20	0.08	−0.01
Globigerinella aequilateralis	**0.57**	**0.53**	**0.71**	0.04	0.05	0.08
	DOT January			DOT July		
	H ($N=114$)	M ($N=40$)	L ($N=15$)	H ($N=114$)	M ($N=40$)	L ($N=15$)
Globigerinoides ruber	−0.10	0.26	0.35	−0.08	**0.40**	0.28
Globigerinoides sacculifer	−0.13	0.12	−**0.49**	−0.12	−0.04	−**0.47**
Globigerinita glutinata	−0.15	**0.33**	0.22	−0.20	**0.34**	0.21
Neogloboquadrina dutertrei	**0.45**	0.02	−0.42	**0.46**	−0.09	−0.43
Pulleniatina obliquiloculata	**0.55**	−0.03	−0.25	**0.52**	−0.13	−0.32
Globigerina bulloides	0.29	0.16	**0.90**	0.25	0.03	**0.93**
Globorotalia menardii	−**0.44**	−**0.47**	−0.41	−**0.45**	−**0.36**	−**0.47**
Globigerinella aequilateralis	−**0.33**	−0.09	−0.17	−0.26	−0.12	−0.14

The correlation coefficients are calculated for three subsets of coretops of different preservation. The correlations in bold and underline types are significant values ($\alpha=0.05$). A critical value of correlation 0.30 is determined for high- and medium-preservation subsets, and a critical value of 0.44 is determined for low-preservation subset, based on Spearman's rank correlation coefficient (Conover, 1980).
H = High-preservation subset.
M = Medium-preservation subset.
L = Low-preservation subset.

tant in the control of the abundance patterns of planktonic foraminifers, having significant relationships with the same species, as well as exhibiting faunal-specific control. Overall, this experiment indicates that the SST and DOT seem to be equally important to SCS planktonic foraminifer species. These results not only support previous studies that identified SST as an important factor in faunal distribution patterns, but reveal that the DOT is also an important environmental control to planktonic foraminifers in the SCS. This supports earlier observations in open oceans revealing a relationship between faunal responses and changes in DOT (Ravelo et al., 1990; Brock et al., 1992; Chen, 1994b).

5. Discussion: faunal abundance and correlation patterns

Interpreting the degree of correlation between faunal abundances and ocean hydrographic variables is a primary tool in paleoestimation. A significantly high correlation with an environmental variable (Table 5) is indicative of an important ecological control in faunal distribution. This correlation analysis, however, could be sensitive to the distribution pattern of the samples selected for this study (Le, 1992). The coretop samples used in the present analysis were largely from the northern and southern parts of the SCS. Few data have been obtained from the central SCS, which displays strong carbonate dissolution conditions probably due to its deep water depth (≥3000 m). So there is a minor possibility that interpretations of the correlations in this study may be biased by the uneven distribution pattern of the coretop samples.

In the SCS, regional patterns of SST and DOT are clearly uncoupled: SST shows a distinct north–south gradient in January only (Fig. 2), and DOT exhibits an east–west pattern in general (Fig. 4). This uncorrelated pattern provides a good opportunity to distinguish between the effects of these two hydrographic variables. Based on the results from the above statistical analyses, the ecological significance of these variables on the eight dominant planktonic foraminifer species will be discussed. Since there is a lack of SST gradient during July, we do not expect any correlation between the assemblage and the SST. We suggest that four ecological groups can be identified as Recent SCS planktonic foraminifers: Group I – faunas primarily reliant on DOT, with positive correlations (*N. dutertrei*), Group II – faunas reliant on both SST and DOT, showing negative correlations with SST and positive correlations with DOT (*G. glutinata*, *P. obliquiloculata*, and *G. bulloides*, Group III – faunas reliant on both SST and DOT, showing positive correlations with SST and negative correlations with DOT (including *G. sacculifer*, *G. menardii*, and *G. aequilateralis*), and Group IV – faunas reliant on both SST and DOT, with positive correlations (*G. ruber*).

In Group I, the abundance of *N. dutertrei* showed a significant positive correlation with DOT. High abundances of this species seem to be an indication of strong mixing and upwelling in the SCS. In fact, *N. dutertrei* has been found to be a dominant species in southern Taiwan strait (Chen and Kuo, 1986; Huang, 1990; Yin, 1991), where strong winter upwelling occurs due to the intrusion waters from the Kuroshio Current (Shaw, 1989, 1991; Shaw et al., 1996). This upwelling causes strong mixing in the oceanic upper-layer and create a deep DOT down to about 175–225 m in the northern SCS (Fig. 4). *N. dutertrei* is closely associated with the surface water upwelling during the summer monsoon season in the Arabian Sea (Cullen, 1981; Duplessy et al., 1981) and in the Panama Basin (Fairbanks et al., 1982). In open oceans, *N. dutertrei* is also abundant in major divergence regions of equatorial current systems (Bé and Tolderlund, 1971; Bé, 1977). In the Bay of Bengal (Cullen and Prell, 1984) and the western continental margin of India (Divakar Naidu, 1993), *N. dutertrei* has been identified as an index of low-salinity waters.

In Group II, The high abundances of *G. glutinata*, *P. obliquiloculata*, and *G. bulloides* are associated with cold surface waters and deep thermocline depths. In the SCS, these three species are most abundant north of the basin, near the shelf area of southern China, where strong winter monsoon winds cause surface waters cold and well-mixed (Shaw and Chao, 1994). The wind effect also creates a nearly-homogenized oceanic upper-layer which is reflected by a relatively deep DOT of about 150 m (Fig. 4). In the Pacific, the distribution of *G. glutinata* is mostly found in the subtropics (Bé, 1977), and in the Panama Basin, high fluxes of this species are associated with deep mix layer conditions (Fairbanks et al., 1982; Thunell and Reynolds, 1984). DOT appeared to be a dominant control in the abundance of *P. obliquiloculata*. In the western Pacific, *P. obliquiloculata* seems to be primarily associated with a DOT of about 200 m (Chen, 1994b). In the Indian Ocean, *P. obliquiloculata* is associated with the South Equatorial and Somali Current systems (Bé and Hutson, 1977). *G. bulloides* is a subpolar species living in cold and deep-mixing surface waters, and is also abundant in strong upwelling oceans over the monsoon regions of the Arabian Sea (Prell, 1984). The abundance of *G. bulloides* is also used as a measure of productivity in western Indian coastal upwelling areas (Divakar Naidu et al., 1992). These previously reported relationships are consistent with those seen in the present study in the SCS.

The abundances of faunal species in Group III (*G. sacculifer*, *G. menardii*, and *G. aequilateralis*) show positive correlations with SST and negative correlations with DOT, indicating that these species are abundant in warm and less-mixing surface ocean conditions. In the SCS, these conditions are in the west of the basin and northwestern Palawan area. In other regions, earlier studies of the distribution of *G. sacculifer* indicate a preference for warm waters (Bé and Tolderlund, 1971; Bé, 1977). Culture experiments (Hemleben et al., 1989) have also demonstrated that *G. sacculifer* is more affected by the conditions of feeding frequency and light quality. Since the nutrient fluxes in the photic zone in the upper-layer waters are largely controlled by the position of the DOT, the negative correlation between the abundance of *G. sacculifer* and DOT may imply productivity control of this species. The ecological preference of *G. menardii* as suggested by this study is consistent with the idea that *G. menardii* prefers living in tropical waters (Bé, 1977); though, this species is also associated with strong current systems or shallow thermocline in the Panama Basin, eastern Pacific Ocean (Thunell and Reynolds, 1984). The preference of *G. aequilateralis* for warm surface waters has been reported in studies in the Panama Basin (Thunell and Reynolds, 1984). No previous work, however, has demonstrated a close association between the high abundance of this species and the shallow DOT. The correlation between the abundance of *G. aequilateralis* and DOT was significant in the present study ($r = -0.33$ in the high-preservation subset; Table 5), though this may not be conclusive since it was close to the critical value (0.30) and has not been previously reported.

In Group IV, the high abundances of *G. ruber* are associated with high SST and deep DOT. In the SCS, these conditions are in the southwest of the basin in the Sunda shelf, along the northern coast of Borneo, and in the Palawan–Sulu Sea, primarily shallow sea area. In general, previous studies in other regions revealed *G. ruber* to be a typical tropical species preferring the environment of warm surface water and deep DOT (Bé, 1977; Fairbanks et al., 1982; Ravelo et al., 1990). Due to the high correlation between the abundance of this species and water depth ($r = -0.42$, in Table 4), we cannot rule out the possibility of a major preservation imprint on the relationship in the SCS.

6. Conclusions

In the SCS, variations in the abundance of planktonic foraminifers in modern surface sediments are linked to hydrographic variables of seasonal SST and DOT. By adopting correlation analyses of 173 SCS coretop data, many notable relationships are identified and may indicate that the seasonal variables of SST and DOT are of approximately equal importance. With a division of the data set based on different carbonate preservation levels, these relationships show the following.

(1) The abundance of *N. dutertrei* is significantly correlated with DOT. High abundances of the species can be used as measures for upwelling waters in the SCS.

(2) The high abundances of *G. glutinata*, *P. obliquiloculata*, and *G. bulloides* indicate cold surface waters and deep thermocline depths in the SCS. The abundances of these species can be used to indicate cold and strong mixing conditions caused by prevailing northeast monsoon winds during the winter.

(3) The abundances of *G. sacculifer*, *G. menardii*, and *G. aequilateralis* in the SCS exhibit a significant positive correlation with SST and a negative correlation with DOT. High abundances of these species indicate warm and less-mixing surface ocean conditions in the SCS.

(4) High abundances of *G. ruber* are associated with high SST and deep DOT. The distribution pattern of this species maybe also controlled by preservation.

(5) High correlations between water depths and the abundances of *G. ruber* and *G. menardii* indicate a possible preservation control on the species distribution patterns.

This study indicates that in the SCS, correlations between the faunal abundances of planktonic foraminifers and SST or DOT are about equally significant. This would suggest that faunal abundances of planktonic foraminifers in modern surface sediments maybe also controlled by the vertical structure of the oceanic upper-layers. Furthermore, these analyses demonstrate the usefulness of faunal abundances of planktonic foraminifers in estimating not only past ocean SST, but DOT changes as well. These results are consistent with similar works in the low-latitude Pacific (Ravelo et al., 1990; Brock et al., 1992; Chen, 1994b), yet by no means do we suggest that SST and DOT are the only critical factors in faunal distribution patterns. Certainly, more coretop data from a wider geographic area, and higher resolution hydrographic data of other environmental variables, including sea-surface salinity, depth of halocline, and nutrient concentrations, will be needed for more complete analyses in the future.

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