Sea Surface Temperature Estimates for the Mid-Piacenzian Indian Ocean—Ocean Drilling Program Sites 709, 716, 722, 754, 757, 758, and 763

By Marci M. Robinson, Harry J. Dowsett, and Danielle K. Stoll

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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)
	Volume	
liter (L)	33.81402	ounce, fluid (fl. oz)
liter (L)	2.113	pint (pt)
liter (L)	1.057	quart (qt)
liter (L)	0.2642	gallon (gal)
cubic meter (m^3)	264.2	gallon (gal)
cubic decimeter (dm^3)	0.2642	gallon (gal)
cubic centimeter (cm^3)	0.06102	cubic inch (in^3)
liter (L)	61.02	cubic inch (in^3)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
	Density	
gram per cubic centimeter (g/cm^3)	62.4220	pound per cubic foot (lb/ft^3)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as °F = (1.8 × °C) + 32.
Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as °C = (°F – 32) / 1.8.

Abbreviations

BFD	Brown University Foraminiferal Database
IODP	International Ocean Discovery Program
MAT	modern analog technique
NCEI	National Centers for Environmental Information
ODP	Ocean Drilling Program
PRISM	Pliocene Research, Interpretation and Synoptic Mapping
SCD	squared chord distance
SST	sea surface temperature
USGS	U.S. Geological Survey

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Introduction

Despite the wealth of global paleoclimate data available for the warm period in the middle of the Piacenzian Stage of the Pliocene Epoch (about 3.3 to 3.0 million years ago [Ma]; Dowsett and others, 2013, and references therein), the Indian Ocean has remained a region of sparse geographic coverage in terms of microfossil analysis. In an effort to characterize the surface Indian Ocean during this interval, we examined the planktic foraminifera from Ocean Drilling Program (ODP) sites 709, 716, 722, 754, 757, 758, and 763, encompassing a wide range of oceanographic conditions. We quantitatively analyzed the data for sea surface temperature (SST) estimation using both the modern analog technique (MAT) and a factor analytic transfer function. The data will contribute to the U.S. Geological Survey (USGS) Pliocene Research, Interpretation and Synoptic Mapping (PRISM) Project's global SST reconstruction and climate model SST boundary condition for the mid-Piacenzian and will become part of the PRISM verification dataset designed to ground-truth Pliocene climate model simulations (Dowsett and others, 2013).

Materials and Methods

ODP sites 709, 716, 722, 754, 757, 758, and 763 cover the Indian Ocean north of 40° S., with average spacing between sites of less than 10° in both latitude and longitude (fig. 1, table 1). We focused our analysis on the warm interval of the mid-Piacenzian as described in Dowsett and others (2013). Age models used to determine the age of samples at each site are listed in table 1.

Micropaleontological Analyses

Mid-Piacenzian core material was sampled for quantitative planktic foraminiferal faunal analyses. Samples of 20 cubic centimeters (cm^3) from site 754, originally collected for ostracod trace metal analysis, and 10 cm^3 from all other sites were oven dried at ≤50 degrees Celsius (°C). Dried bulk samples were disaggregated in 250 milliliters (ml) of warm tap water with about 50 ml of dilute sodium hexametaphosphate (5 grams per liter water). Samples were then agitated for 1 hour at about 21 °C and washed over a 150-micrometer sieve using a fine spray hose. The coarse fraction was dried in an oven at ≤50 °C. Some samples required an additional wash in order to obtain clean specimens. The sample was split using a precision microsplitter to obtain 300 to 350 specimens for analysis. Most samples required 8 to 10 splits to achieve 300 to 350 specimens. Foraminifera were least abundant at sites 722 and 758 where one-half to all of the specimens were picked for analysis. Individual specimens were identified to species level, generally following the taxonomy of Parker (1962, 1967) and Blow (1969) with modifications (Dowsett and Robinson, 2007), and glued to a 60-square micropaleontological slide.

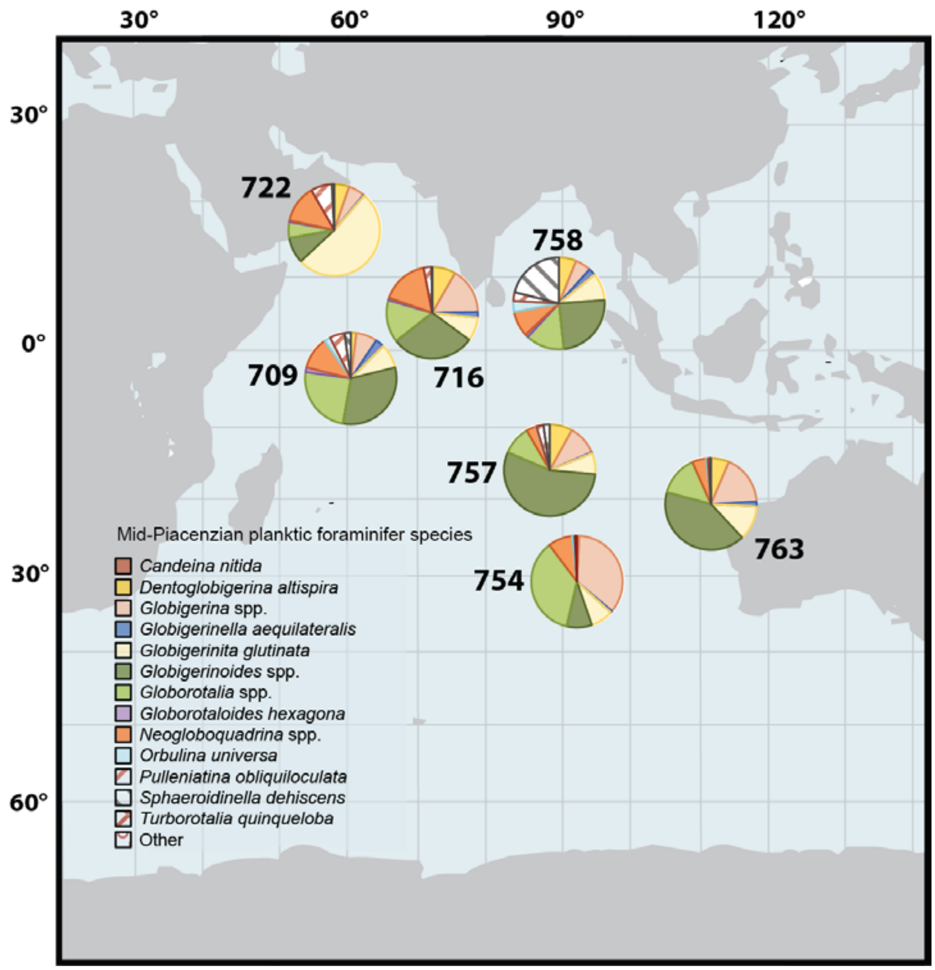

Figure 1. Map showing locations of Ocean Drilling Program sites 709, 716, 722, 754, 757, 758, and 763 described in this study and mean mid-Piacenzian planktic foraminifer species distribution at those sites.

Table 1. Site information for Ocean Drilling Program sites 709, 716, 722, 754, 757, 758, and 763 described in this study.

[ODP, Ocean Drilling Program; m, meter]

ODP site	Latitude	Longitude	Water depth (m)	Age model reference
709	3.92° S.	60.55° E.	3,038	Karas and others, 2011
716	4.93° N.	73.28° E.	544	Rio and others, 1990
722	16.62° N.	59.80° E.	2,028	Herbert and others, 2010
754	30.93° S.	93.57° E.	1,064	Shipboard Scientific Party, 1989a
757	17.02° S.	88.18° E.	1,652	Shipboard Scientific Party, 1989b
758	5.38° N.	90.37° E.	2,924	Farrell and others, 1995
763	20.59° S.	112.21° E.	1,368	Karas and others, 2011

Modern Analog Technique

The modern analog technique quantifies faunal changes within deep sea cores in terms of modern oceanographic conditions (Hutson, 1980). The method uses a measure of faunal dissimilarity to compare downcore samples to each reference sample in a modern faunal database. We chose the following squared chord distance (SCD) measure for our study:

$$d_{ij} = \Sigma_k \left(p_{ik}^{0.5} - p_{jk}^{0.5} \right)^2$$

where d_{ij} is the squared chord distance between two multivariate samples i and j, p_{ik} is the proportion of species k in sample i, and p_{jk} is the proportion of species k in sample j. Squared chord distance values can range from 0.0 to 2.0, with 0.0 indicating identical proportions of species in the samples being compared.

Table 2. Taxonomic counting categories used in this study.

Taxon	Maximum occurrence (percent of sample)
Globigerinoides ruber	57.7
Globigerinoides sacculifer	24.8
Globigerinita glutinata	41.7
Globigerinella aequilateralis	9.1
Neogloboquadrina dutertrei	35.0
Globigerina calida	8.8
Globigerina bulloides	62.2
Pulleniatina obliquiloculata	20.8
Globigerinoides conglobatus	8.1
Globorotalia truncatulinoides (dextral)	10.5
Globigerina falconensis	19.5
Globorotaloides hexagona	8.0
Globigerinoides tennellus	7.7
Globigerina rubescens	5.2
Orbulina universa	4.5
Globorotalia truncatulinoides (sinistral)	12.9
Beella digitata	12.7
Neogloboquadrina pachyderma (sinistral)	97.5
Globorotalia crassaformis	4.4
Candeina nitida	1.7
Globorotalia menardii flexuosa	2.2
Globorotalia hirsuta	4.4
Sphaeroidinella dehiscens	5.6
Turborotalita humilis	1.1
Turborotalita quinqueloba	16.5
Hastigerina adamsi	0.7
Neogloboquadrina “du-pac”	27.0
Globorotalia tumida	23.5
Globorotalia menardii	65.8
Neogloboquadrina pachyderma (dextral)	29.4
Globorotalia inflata	83.6

Census data from the mid-Piacenzian Indian Ocean samples were compared to census data from 279 modern core-top Indian Ocean samples of the Brown University Foraminiferal Database (BFD) surface dataset (Prell and others, 1999). We revised the modern planktic foraminifer data into categories that retained most of the primary temperature signal but also provided a good fit to mid-Piacenzian assemblages. The modern taxa were reduced to 33 mid-Piacenzian counting categories by combining taxa that have documented similar environmental tolerances (table 2), following Dowsett and Poore (1990) and Dowsett (1991). Modern cold and warm season SSTs at all core locations were calibrated to the Reynolds and Smith (1995) modern surface temperature dataset (see Dowsett and Poore, 1990; Dowsett, 1991).

Factor Analytic Transfer Function

Census data from the same BFD samples as used in the MAT were used to construct a factor analytic transfer function to document and compare the spatial distribution of modern and Pliocene taxa. The modern taxa, regrouped as for the MAT, were quantitatively analyzed using a Q-mode factor analysis approach in order to determine interrelationships between samples. Our analysis identified five primary factors (F1–F5) that accounted for 92% of the total variance in the dataset (table 3). The relative importance of each of the 33 counting categories (used here as factor analytic variables) to each factor is presented in the factor score matrix. The counting categories with the greatest contribution to the F1 assemblage are *Globigerinoides ruber*, *Globigerinoides sacculifer*, *Globigerinita glutinata*, and *Globorotalia menardii*. The F2 assemblage has important contributions from *Globigerinita glutinata*, *Globigerina bulloides*, and *Neogloboquadrina pachyderma* (sinistral). The counting category with the highest scores in the F3 assemblage is *Globorotalia menardii*, followed by *Neogloboquadrina dutertrei*, *Pulleniatina obliquiloculata*, *Globigerinoides sacculifer*, and *Globigerinoides ruber*. The F4 assemblage is dominated by *Globorotalia inflata*, followed by lesser contributions from *Neogloboquadrina pachyderma* (dextral and sinistral). The F5 assemblage is quantitatively dominated by *Neogloboquadrina pachyderma* (sinistral), *Globigerina bulloides*, and *Globigerinita glutinata*. Based on the geographic distribution of characteristic species, we categorize the five primary factors as subtropical (F1), boundary current (F2), tropical (F3), transitional between subtropical and subpolar (F4), and polar-subpolar (F5).

Calibration of the five modern factors to February and August SST resulted in two 20-term equations and an intercept that related the five varimax assemblages to cold and warm season SST. Both seasons had an R^2 value of 0.98 and standard errors of 1.2 °C (February) and 1.4 °C (August). Collectively, these equations are referred to as GSF36. To apply GSF36 to the mid-Piacenzian planktic foraminifer assemblages, the raw faunal data were grouped into 33 counting categories like the core-top data. Some Pliocene taxa, however, are now extinct and were not explicitly included in the counting categories. We made the assumption that closely related taxa (ancestor-descendent pairs) have similar ecological tolerances and preferences (see Dowsett and Poore, 1990; Dowsett, 1991; Kucera and Schönfeld, 2007; Waterson and others, 2017).

Table 3. Varimax assemblage description matrix showing the relative importance of each of the 33 variables (planktic foraminifer species) to each of the five primary factors (F1–F5). Together, these five factors explain 92 percent of the planktic foraminifer assemblage variance in the modern core-top data.

[The strongest associations between variables and primary factors are shown in bold.]

Variable (planktic foraminifer species)	Primary factor				
	F1	F2	F3	F4	F5
Globigerinoides ruber	**5.1572**	-0.3653	**-0.4205**	0.5170	-0.0123
Globigerinoides sacculifer	**1.9042**	-0.6802	**1.0439**	-0.2810	0.5983
Globigerinita glutinata	**1.0232**	**4.3010**	-0.2453	-0.3559	**-1.6200**
Globigerinella aequilateralis	0.5664	-0.2044	0.4744	0.0879	0.1171
Neogloboquadrina dutertrei	0.6545	0.2719	**2.5131**	-0.1245	0.2019
Globigerina calida	0.3925	-0.0649	0.0725	0.0994	0.0162
Globigerina bulloides	-0.2865	**3.5113**	0.0108	0.8992	**3.2025**
Pulleniatina obliquiloculata	0.3784	0.1180	**1.0520**	-0.2044	0.0629
Globigerinoides conglobatus	0.3098	-0.2324	0.3020	-0.0118	0.1368
Globorotalia truncatulinoides (dextral)	0.1357	-0.1214	-0.0292	0.2808	-0.0518
Globigerina falconensis	0.0263	0.5766	-0.1313	0.4136	-0.3587
Globorotaloides hexagona	0.2442	0.0401	0.1146	-0.0968	0.0635
Globigerinoides tennellus	0.1884	0.1444	-0.0766	-0.0329	-0.0443
Globigerina rubescens	0.1397	0.1255	-0.0532	-0.0199	-0.0407
Orbulina universa	0.1127	-0.0255	0.0174	0.1606	-0.0112
Globorotalia truncatulinoides (sinistral)	0.0006	-0.0345	-0.0395	0.8594	0.1265
Neogloboquadrina conglomerata	0.1853	-0.2252	0.6082	-0.0789	0.2340
Globorotalia scitula	0.0780	0.0106	-0.0135	0.0783	-0.0115
Beella digitata	0.0444	-0.0490	0.2092	0.0704	-0.0131
Neogloboquadrina pachyderma (sinistral)	0.2318	**-0.8255**	0.0238	**-0.5625**	**4.3590**
Globorotalia crassaformis	0.0298	-0.0242	0.0431	0.0088	0.0104
Candeina nitida	0.0215	-0.0104	-0.0037	0.0029	0.0074
Globorotalia menardii flexuosa	0.0091	0.0013	0.0315	-0.0041	0.0059
Globorotalia hirsuta	0.0170	-0.0381	0.0076	0.2196	-0.0698
Sphaeroidinella dehiscens	0.0029	-0.0398	0.1684	0.0021	0.0237
Turborotalita humilis	0.0046	-0.0012	0.0002	-0.0001	0.0012
Turborotalita quinqueloba	-0.0169	0.0181	-0.0111	0.0255	0.3595
Hastigerina adamsi	0.0021	0.0015	-0.0010	-0.0007	0.0002
Neogloboquadrina “du-pac”	-0.0847	0.0738	0.0456	0.6074	0.3578
Globorotalia tumida	-0.1253	0.0588	0.6445	0.0445	-0.1128
Globorotalia menardii	**-0.4219**	0.2478	**4.7976**	0.1112	-0.4091
Neogloboquadrina pachyderma (dextral)	-0.1449	0.0494	0.0284	**1.2607**	-0.0976
Globorotalia inflata	-0.1979	-0.4358	0.0786	**5.3163**	-0.1430
Variance	34.304	21.098	19.030	10.470	7.101
Cumulative variance	34.304	55.402	74.432	84.902	92.003

Results and Discussion

Planktic Foraminiferal Assemblage Data

Planktic foraminifer census data from the mid-Piacenzian Indian Ocean sites (Dowsett and others, 2015) can be accessed at the National Oceanic and Atmospheric Administration's National Centers for Environmental Information (NCEI) (Foley and others, 2015; https://www.ncdc.noaa.gov/paleo/study/19281). Figure 1 shows the geographic distribution of species in terms of mean percentage at each site, and figure 2 displays time series percent data for the mid-Piacenzian interval of each Indian Ocean site. In general, the mid-Piacenzian tropical Indian Ocean was characterized by an abundance of *Globigerinoides* species and *Globorotalia menardii*. Site 722, located in a tropical upwelling zone, was dominated by *Globigerinita glutinata*.

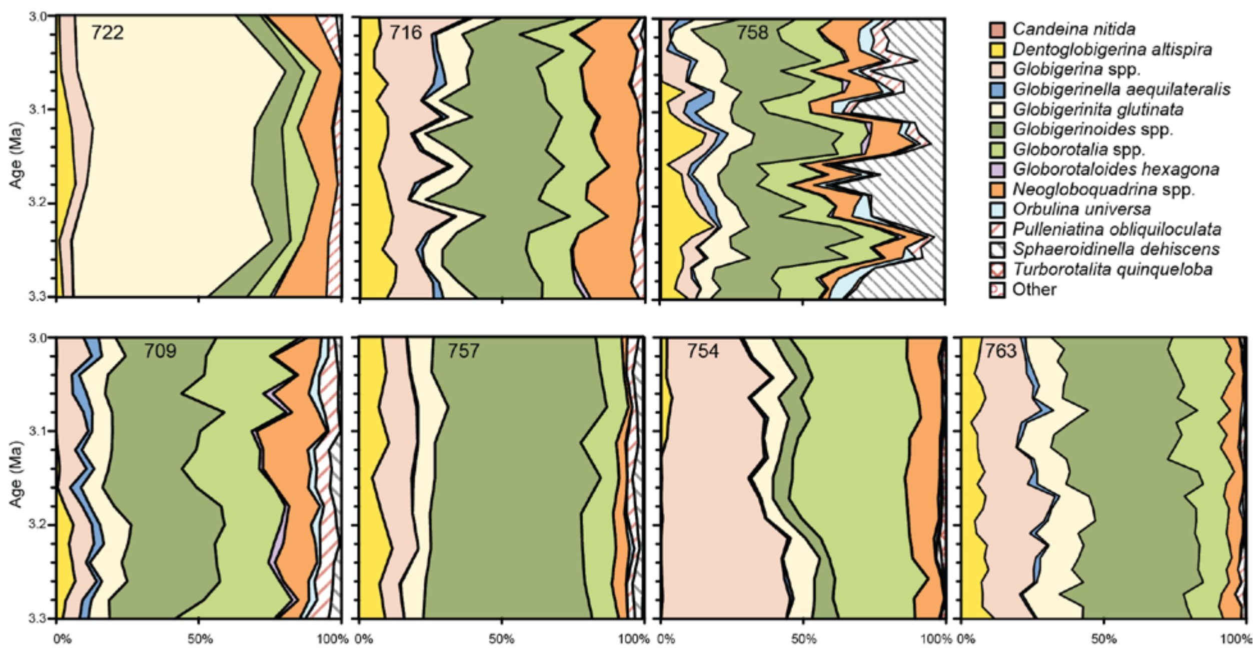

Figure 2. Time series plots of mid-Piacenzian planktic foraminifer species assemblages by percentage for Ocean Drilling Program sites 709, 716, 722, 754, 757, 758, and 763 in the Indian Ocean, arranged geographically.

Modern Analog Technique

The modern analog technique performed adequately at five of the seven low- to mid-latitude Indian Ocean sites. Squared chord distances to the nearest modern analog are ≤0.34 for all samples from sites 709, 716, 722, 757, and 763, with the vast majority within a distance of 0.20 (table 4). Cold and warm season SST estimates are shown in table 4. Most samples from ODP sites 754 and 758 showed higher dissimilarity, indicating an absence of analogous faunas in the modern Indian Ocean. Because faunal census data from sites 754 and 758 are predominantly non-analog assemblages, we have reduced confidence in the resulting SST estimates.

Factor Analytic Transfer Function

Estimates of SST were obtained using GSF36 for mid-Piacenzian Indian Ocean samples from ODP sites 709, 716, 722, 754, 758, and 763 (fig. 3). Cold and warm season SST estimates are shown in table 4. GSF36 factors provide a quantitative picture of the assemblage composition of each sample. Factor loadings indicate a strong relationship between mid-Piacenzian samples from site 709 and both tropical and subtropical assemblages and a strong relationship between site 763 samples and subtropical assemblages. GSF36 functioned very well at these two sites with all samples returning a communality of ≥0.7 (that is, 84 percent or more of the information was explained by the core-top factor model). For site 716, 74 percent of samples had acceptable communalities. All but one of these samples were tied to subtropical assemblages; the remaining sample (at 3.02 Ma) was more closely related to a tropical assemblage. Site 722 mid-Piacenzian samples are most closely related to boundary current assemblages, and site 754 samples are most closely related to transitional assemblages, although only 67 percent and 30 percent of samples, respectively, showed communalities ≥0.7. GSF36 could deliver meaningful oceanographic estimates for only seven percent of site 758 samples; the remaining samples had no modern analogs. Those few samples, however, did show a clear relationship to subtropical assemblages.

Table 4. Cold and warm season sea surface temperature (SST) estimates for samples using the modern analog technique with squared chord distance (SCD) values and the factor analytic transfer function GSF36 with communalities.

[cm, centimeter; mbsf, meters below sea floor; Ma, million years ago; °C, degree Celsius; ODP, Ocean Drilling Program]

Sample	Depth (mbsf)	Age (Ma)	Modern analog technique			Factor analytic transfer function		
			Cold SST (°C)	Warm SST (°C)	SCD	Cold SST (°C)	Warm SST (°C)	Communality
ODP site 709, hole C								
4H-2, 42–44 cm	27.02	2.83	26.17	29.11	0.14	26.7	27.8	0.8886
4H-2, 57.5–59.5 cm	27.18	2.85	26.17	29.11	0.11	26.7	27.4	0.9028
4H-2, 83–85 cm	27.43	2.88	26.17	29.11	0.10	27.2	28.7	0.9095
4H-2, 102.5–104.5 cm	27.63	2.90	26.17	29.11	0.10	27.3	28.3	0.8495
4H-2, 112.5–114.5 cm	27.73	2.91	4.47	7.59	0.14	27.3	27.9	0.8852
4H-2, 132–134 cm	27.92	2.93	26.17	29.11	0.10	27.7	28.2	0.8455
4H-2, 142–144 cm	28.02	2.95	26.17	29.11	0.13	27.5	28.0	0.8988
4H-3, 2–4 cm	28.12	2.96	26.17	29.11	0.06	27.7	28.6	0.9550
4H-3, 17–19 cm	28.27	2.97	24.41	29.11	0.10	27.6	28.7	0.8547
4H-3, 33–35 cm	28.43	2.99	26.17	29.11	0.15	27.1	27.7	0.9074
4H-3, 46–49 cm	28.56	3.01	24.34	27.78	0.14	27.6	28.1	0.9262
4H-3, 57.5–59.5 cm	28.68	3.02	26.17	29.11	0.12	27.3	27.9	0.9327
4H-3, 83–85 cm	28.93	3.05	26.17	29.11	0.15	27.1	28.3	0.8523
4H-3, 93.5–95.5 cm	29.04	3.06	24.77	25.00	0.12	28.5	29.2	0.8086
4H-3, 117.5–119.5 cm	29.28	3.09	24.57	25.93	0.09	28.5	29.1	0.8345
4H-3, 132.5–134.5 cm	29.43	3.11	25.47	27.06	0.11	27.6	28.6	0.8933
4H-3, 142–144 cm	29.52	3.12	26.17	29.11	0.11	27.1	28.5	0.8226
4H-4, 7–9 cm	29.67	3.14	26.17	29.11	0.14	27.7	28.5	0.7835
4H-4, 17–19 cm	29.77	3.19	8.93	10.48	0.15	28.0	28.4	0.8178
4H-4, 32–34 cm	29.92	3.25	26.17	29.11	0.15	27.9	28.7	0.7544
4H-4, 46.5–48.5 cm	30.07	3.31	25.04	27.07	0.23	28.1	28.9	0.7894

Table 4. Cold and warm season sea surface temperature (SST) estimates for samples using the modern analog technique with squared chord distance (SCD) values and the factor analytic transfer function GSF36 with communalities.—Continued

[cm, centimeter; mbsf, meters below sea floor; Ma, million years ago; °C, degree Celsius; ODP, Ocean Drilling Program]

Sample	Depth (mbsf)	Age (Ma)	Modern analog technique			Factor analytic transfer function		
			Cold SST (°C)	Warm SST (°C)	SCD	Cold SST (°C)	Warm SST (°C)	Commu nality
ODP site 716, hole B								
11-3, 54–56 cm	94.24	2.95	25.00	28.91	0.25	27.8	27.8	0.6248
11-3, 128–130 cm	94.98	2.97	26.17	29.11	0.30	27.5	27.7	0.5587
11-4, 58–60 cm	95.78	2.98	3.02	5.70	0.24	28.2	28.3	0.6876
11-4, 139–141 cm	96.59	3.00	3.02	5.70	0.25	27.0	26.6	0.4764
11-5, 68–70 cm	97.38	3.02	24.34	27.78	0.19	27.5	28.3	0.7561
11-6, 1–3 cm	98.21	3.03	3.02	5.70	0.15	28.1	28.3	0.7555
11-6, 84–86 cm	99.04	3.05	25.18	28.44	0.24	28.0	28.7	0.6858
11-7, 9–11 cm	99.79	3.07	26.65	28.25	0.18	28.4	29.1	0.7260
12-1, 27–29 cm	100.58	3.08	26.65	28.25	0.14	28.7	29.0	0.8381
12-1, 113–115 cm	101.44	3.10	26.65	28.25	0.14	28.3	28.3	0.7944
12-2, 37–39 cm	102.18	3.12	26.65	28.25	0.11	29.1	29.3	0.8156
12-2, 117–119 cm	102.98	3.13	26.65	28.25	0.15	28.0	28.8	0.8441
12-3, 53–55 cm	103.84	3.15	3.02	5.70	0.16	28.4	28.8	0.7780
12-3, 127–129 cm	104.58	3.17	26.41	28.68	0.22	27.4	27.6	0.7948
12-4, 57.5–59.5 cm	105.39	3.18	26.65	28.25	0.18	28.4	28.1	0.8648
12-4, 137.5–139.5 cm	106.19	3.20	3.02	5.70	0.20	28.2	28.4	0.7339
12-5, 67–69 cm	106.98	3.22	26.65	28.25	0.20	27.8	28.5	0.8343
12-6, 3–5 cm	107.84	3.23	26.41	28.68	0.27	27.7	27.2	0.6949
12-6, 84–86 cm	108.65	3.25	26.65	28.25	0.22	28.2	27.9	0.7693
12-7, 7–9 cm	109.38	3.27	25.83	28.58	0.18	28.6	29.0	0.8309
13-1, 97.5–99.5 cm	110.99	3.30	3.02	5.70	0.18	27.3	27.9	0.8107
13-2, 34–36 cm	111.85	3.32	25.50	28.02	0.24	27.8	27.1	0.7653
13-2, 113–115 cm	112.64	3.33	24.34	27.78	0.21	27.9	28.4	0.7810
ODP site 722, hole A								
10X-3, 10–12 cm	88.61	2.85	6.06	7.63	0.18	27.3	27.4	0.7306
10X-3, 110–112 cm	89.61	2.88	24.86	26.40	0.13	27.7	28.2	0.5446
10X-4, 10–12 cm	90.11	2.90	26.58	26.87	0.17	28.0	28.2	0.6819
10X-4, 110–112 cm	91.11	2.94	27.47	27.60	0.27	26.7	27.5	0.6650
10X-5, 10–12 cm	91.61	2.96	6.06	7.63	0.34	26.2	28.1	0.5525
11X-1, 12–14 cm	95.33	3.09	24.44	24.78	0.22	25.6	28.4	0.6898
11X-1, 108–110 cm	96.29	3.11	24.44	24.78	0.17	23.3	29.1	0.7410
11X-2, 8–10 cm	96.79	3.13	25.04	25.93	0.18	24.0	29.0	0.7231
11X-2, 112–114 cm	97.83	3.16	6.06	7.63	0.28	23.9	28.6	0.7144
11X-3, 112–114 cm	99.33	3.23	25.37	26.28	0.16	24.6	28.3	0.7322
ODP site 754, hole A								
2-4, 1–5 cm	10.61	2.71	23.88	27.60	0.27	15.7	21.5	0.7461
2-4, 14–18 cm	10.74	2.73	8.18	10.55	0.30	15.6	21.6	0.7435
2-4, 29–33 cm	10.89	2.75	23.88	27.60	0.29	16.5	22.1	0.5860
2-4, 44–48 cm	11.04	2.77	21.85	26.46	0.34	15.8	21.4	0.5626
2-4, 59–63 cm	11.19	2.79	23.88	27.60	0.34	16.1	22.2	0.6246

Table 4. Cold and warm season sea surface temperature (SST) estimates for samples using the modern analog technique with squared chord distance (SCD) values and the factor analytic transfer function GSF36 with communalities.—Continued

[cm, centimeter; mbsf, meters below sea floor; Ma, million years ago; °C, degree Celsius; ODP, Ocean Drilling Program]

Sample	Depth (mbsf)	Age (Ma)	Modern analog technique			Factor analytic transfer function		
			Cold SST (°C)	Warm SST (°C)	SCD	Cold SST (°C)	Warm SST (°C)	Communality
ODP site 754, hole A—Continued								
2-4, 74–78 cm	11.34	2.82	23.88	27.60	0.24	16.8	22.7	0.8451
2-4, 89–93 cm	11.49	2.84	23.88	27.60	0.26	16.6	23.4	0.7993
2-4, 104–108 cm	11.64	2.86	23.88	27.60	0.39	16.5	22.7	0.5605
2-4, 119–123 cm	11.79	2.89	23.88	27.60	0.39	16.0	22.1	0.6015
2-4, 134–138 cm	11.94	2.91	23.88	27.60	0.33	16.4	22.9	0.7101
2-5, 0–4 cm	12.10	2.93	23.88	27.60	0.38	15.7	21.5	0.6303
2-5, 14–18 cm	12.24	2.95	23.88	27.60	0.39	17.1	21.7	0.5332
2-5, 29–33 cm	12.39	2.97	23.88	27.60	0.32	16.7	22.3	0.5966
2-5, 44–48 cm	12.54	3.00	23.88	27.60	0.31	16.7	22.4	0.7006
2-5, 59–63 cm	12.69	3.02	23.88	27.60	0.36	17.1	22.4	0.5763
2-5, 74–78 cm	12.84	3.04	23.88	27.60	0.39	17.3	22.4	0.4549
2-5, 89–93 cm	12.99	3.06	23.88	27.60	0.33	16.4	22.6	0.6914
2-5, 104–108 cm	13.14	3.09	23.88	27.60	0.36	16.3	22.1	0.6423
2-5, 119–123 cm	13.29	3.11	23.88	27.60	0.40	16.4	22.2	0.5992
2-5, 134–138 cm	13.44	3.13	23.88	27.60	0.39	16.2	21.5	0.6807
2-6, 0–4 cm	13.60	3.15	23.88	27.60	0.36	16.8	22.4	0.6412
2-6, 14–18 cm	13.74	3.17	23.88	27.60	0.37	16.1	21.9	0.7319
2-6, 29–33 cm	13.89	3.20	23.88	27.60	0.36	16.2	21.6	0.7102
2-6, 44–48 cm	14.04	3.22	21.85	26.46	0.47	15.2	20.9	0.4945
2-6, 59–63 cm	14.19	3.24	23.88	27.60	0.53	15.6	20.5	0.4392
2-6, 74–78 cm	14.34	3.26	23.88	27.60	0.39	15.9	21.3	0.4890
2-6, 89–93 cm	14.49	3.29	23.88	27.60	0.37	16.1	21.5	0.4400
2-6, 104–108 cm	14.64	3.31	23.88	27.60	0.41	16.0	21.3	0.4663
2-6, 119–123 cm	14.79	3.33	23.88	27.60	0.41	15.8	21.5	0.5134
2-6, 134–138 cm	14.94	3.35	23.88	27.60	0.42	16.4	22.1	0.4515
ODP site 757, hole B								
3H-4, 24–26 cm	18.75	2.91	23.32	25.96	0.11	25.2	27.5	0.8788
3H-4, 54–56 cm	19.05	2.96	25.99	27.12	0.12	25.0	27.2	0.8568
3H-4, 84–86 cm	19.35	3.00	0.76	3.01	0.11	24.8	27.6	0.8879
3H-4, 114–116 cm	19.65	3.03	25.99	27.12	0.10	24.0	27.3	0.9330
3H-4, 144–146 cm	19.95	3.07	0.76	3.01	0.12	24.3	27.5	0.9034
3H-5, 24–26 cm	20.25	3.11	25.33	25.99	0.09	25.1	27.7	0.8694
3H-5, 57–59 cm	20.58	3.15	0.76	3.01	0.11	24.3	27.5	0.9100
3H-5, 84–86 cm	20.85	3.19	26.65	28.25	0.12	25.3	27.9	0.7976
3H-5, 109–111 cm	21.10	3.22	25.33	25.99	0.17	24.7	27.6	0.7526
3H-6, 11.5–13.5 cm	21.63	3.28	25.99	27.12	0.11	25.2	27.9	0.8023
3H-6, 29–31 cm	21.80	3.31	25.99	27.12	0.12	25.1	27.9	0.7453
3H-6, 63–65 cm	22.14	3.35	25.33	25.99	0.15	24.7	27.7	0.6974

Table 4. Cold and warm season sea surface temperature (SST) estimates for samples using the modern analog technique with squared chord distance (SCD) values and the factor analytic transfer function GSF36 with communalities.—Continued

[cm, centimeter; mbsf, meters below sea floor; Ma, million years ago; °C, degree Celsius; ODP, Ocean Drilling Program]

Sample	Depth (mbsf)	Age (Ma)	Modern analog technique			Factor analytic transfer function		
			Cold SST (°C)	Warm SST (°C)	SCD	Cold SST (°C)	Warm SST (°C)	Commu nality
ODP site 758, hole A								
5H-3, 7–9 cm	37.88	2.92	24.63	28.16	0.40	27.0	27.0	0.4274
5H-3, 24–25 cm	38.04	2.93	21.41	25.76	0.46	25.1	24.9	0.1294
5H-3, 44–46 cm	38.24	2.95	4.47	7.59	0.31	28.6	29.0	0.5675
5H-3, 65–67 cm	38.45	2.96	4.47	7.59	0.31	29.0	28.0	0.4825
5H-3, 79–81 cm	38.59	2.97	8.93	10.48	0.35	28.9	28.7	0.4640
5H-3, 98.5–100.5 cm	38.79	2.99	26.17	29.11	0.30	28.6	28.9	0.4424
5H-3, 126.5–128.5 cm	39.07	3.00	24.63	28.16	0.18	30.1	29.5	0.7454
5H-3, 142.5–144.5 cm	39.23	3.02	7.87	9.32	0.37	27.7	28.3	0.2704
5H-4, 9.5–11.5 cm	39.40	3.03	24.77	25.00	0.22	29.9	29.6	0.6747
5H-4, 24.5–25.5 cm	39.55	3.05	4.47	7.59	0.30	28.9	28.2	0.4345
5H-4, 48–52 cm	39.78	3.06	25.61	27.20	0.50	25.3	25.6	0.1214
5H-4, 67–69 cm	39.97	3.07	21.41	25.76	0.46	26.3	27.3	0.1793
5H-4, 83–85 cm	40.13	3.08	27.67	28.44	0.24	30.2	30.5	0.5562
5H-4, 107–109 cm	40.37	3.10	24.74	28.17	0.28	29.2	28.8	0.4170
5H-4, 127.5–129.5 cm	40.58	3.11	24.63	28.16	0.18	30.5	30.2	0.6852
5H-5, 5.5–7.5 cm	40.86	3.14	26.65	28.25	0.20	29.8	28.3	0.6942
5H-5, 22–24 cm	41.02	3.15	21.41	25.76	0.53	24.5	25.4	0.1011
5H-5, 37–39 cm	41.17	3.16	6.70	9.04	0.39	28.6	28.4	0.3547
5H-5, 67–69 cm	41.47	3.18	25.42	27.39	0.55	23.7	23.9	0.0824
5H-5, 82–84 cm	41.62	3.20	24.86	27.13	0.39	28.2	27.9	0.2662
5H-5, 95–97 cm	41.75	3.21	21.41	25.76	0.41	27.3	27.0	0.2374
5H-5, 123–125 cm	42.03	3.23	7.87	9.32	0.46	26.1	26.3	0.1610
5H-5, 142.5–144.5 cm	42.23	3.24	28.30	28.62	0.30	28.9	28.7	0.3677
5H-6, 5.5–7.5 cm	42.36	3.27	26.65	28.25	0.24	29.8	29.0	0.5377
5H-6, 27–29 cm	42.57	3.29	26.65	28.25	0.15	30.2	30.0	0.7530
5H-6, 47.5–48.5 cm	42.78	3.31	25.33	25.99	0.21	29.9	29.9	0.5781
5H-6, 65.5–67.5 cm	42.96	3.33	8.93	10.48	0.47	27.8	27.9	0.2418
5H-6, 93–95 cm	43.23	3.35	21.41	25.76	0.42	27.8	27.5	0.2484
5H-6, 107.5–109.5 cm	43.38	3.36	27.01	28.24	0.50	27.5	27.8	0.2105
5H-6, 122.5–124.5 cm	43.53	3.38	21.36	25.84	0.53	26.7	26.5	0.2035
ODP site 763, hole A								
7-7, 9–11 cm	61.50	2.94	3.02	5.70	0.14	24.4	26.5	0.8475
7-7, 45–47 cm	61.86	2.96	0.76	3.01	0.10	24.7	27.1	0.8974
8-1, 9–11 cm	62.00	2.98	26.65	28.25	0.13	26.3	28.0	0.8261
8-1, 26.5–28.5 cm	62.18	2.99	3.02	5.70	0.14	26.2	27.6	0.8057
8-1, 43.5–45.5 cm	62.35	3.00	1.89	4.36	0.10	26.1	27.7	0.8740
8-1, 66–68 cm	62.57	3.01	26.41	28.68	0.11	26.6	27.8	0.8673
8-1, 87–89 cm	62.78	3.01	3.02	5.70	0.15	25.6	26.6	0.8110
8-1, 106–108 cm	62.97	3.02	24.71	27.76	0.13	26.4	27.6	0.8576
8-1, 129–131 cm	63.20	3.03	3.02	5.70	0.10	26.0	27.3	0.8256
8-1, 146.5–148.5 cm	63.38	3.04	3.02	5.70	0.11	27.1	28.3	0.8775
8-2, 9–11 cm	63.50	3.05	25.71	26.63	0.13	26.4	27.7	0.8624

Table 4. Cold and warm season sea surface temperature (SST) estimates for samples using the modern analog technique with squared chord distance (SCD) values and the factor analytic transfer function GSF36 with communalities.—Continued

[cm, centimeter; mbsf, meters below sea floor; Ma, million years ago; °C, degree Celsius; ODP, Ocean Drilling Program]

Sample	Depth (mbsf)	Age (Ma)	Modern analog technique			Factor analytic transfer function		
			Cold SST (°C)	Warm SST (°C)	SCD	Cold SST (°C)	Warm SST (°C)	Commu nality
ODP site 763, hole A—Continued								
8-2, 27–29 cm	63.68	3.06	3.02	5.70	0.09	26.5	27.9	0.8217
8-2, 45–47 cm	63.86	3.07	3.02	5.70	0.13	26.8	27.7	0.8733
8-2, 66–68 cm	64.07	3.08	25.71	26.63	0.11	26.0	27.7	0.8771
8-2, 87–89 cm	64.28	3.08	26.65	28.25	0.10	25.8	27.4	0.8874
8-2, 105–107 cm	64.46	3.09	3.02	5.70	0.13	26.0	27.1	0.8332
8-2, 124–126 cm	64.65	3.10	26.65	28.25	0.09	26.4	28.0	0.8938
8-2, 145–147 cm	64.86	3.11	3.02	5.70	0.06	26.3	28.2	0.9282
8-3, 19–21 cm	65.10	3.12	3.02	5.70	0.11	26.8	27.8	0.7976
8-3, 43–45 cm	65.34	3.12	3.02	5.70	0.13	25.8	27.2	0.7903
8-3, 59–61 cm	65.50	3.13	3.02	5.70	0.08	26.7	27.5	0.8616
8-3, 77.5–79.5 cm	65.69	3.14	3.02	5.70	0.11	26.2	27.5	0.8776
8-3, 100–102 cm	65.91	3.15	3.02	5.70	0.11	25.4	27.4	0.8534
8-3, 119–121 cm	66.10	3.16	3.02	5.70	0.09	26.9	28.1	0.8784
8-3, 139–141 cm	66.30	3.17	26.65	28.25	0.09	25.9	27.9	0.9021
8-4, 9–11 cm	66.50	3.18	3.02	5.70	0.07	26.2	27.7	0.9190
8-4, 27–29 cm	66.68	3.19	26.65	28.25	0.07	26.1	27.7	0.9253
8-4, 47–49 cm	66.88	3.20	3.02	5.70	0.09	26.0	27.2	0.9222
8-4, 79–81 cm	67.20	3.22	3.02	5.70	0.08	25.0	27.2	0.9402

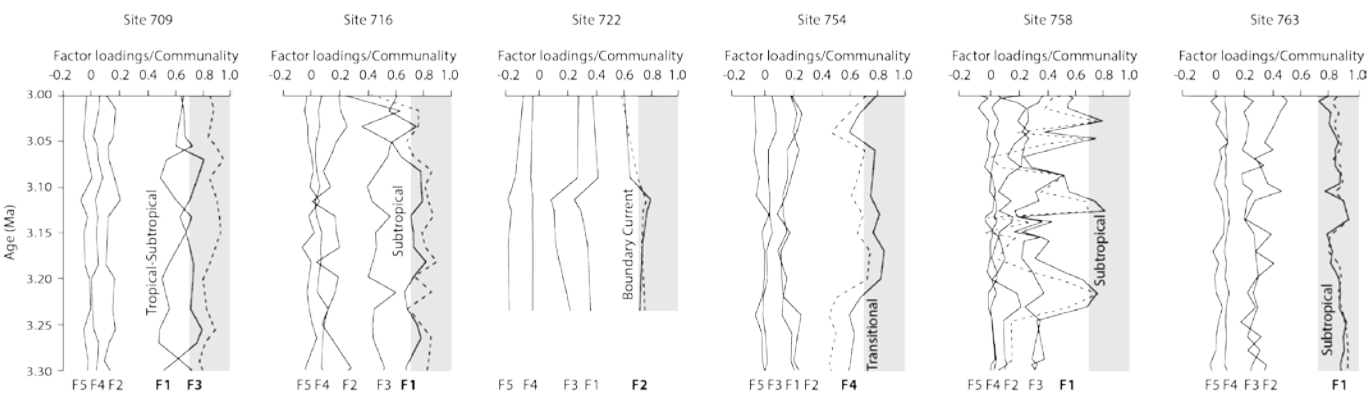

Figure 3. Downcore variation in factor loadings for F1 (subtropical), F2 (boundary current), F3 (tropical), F4 (transitional), and F5 (polar-subpolar) and downcore variation in communality (dashed line) for Ocean Drilling Program sites 709, 716, 722, 754, 758, and 763. Gray band represents the region of acceptable communality of ≥0.7.

Summary and Conclusions

The modern analog technique performed better than the factor analytic transfer function GSF36 in estimating SST within acceptable confidence limits (that is, SCD values <0.2 or communality values ≥0.7) from these Indian Ocean samples. Despite success in estimating sea surface temperature for most mid-Piacenzian Indian Ocean samples, some assemblages from sites 716, 722, 754, and 758 were characterized as having no modern analogs and could not be characterized by GSF36 in terms of assemblages found in the modern ocean. In addition to the lack of good analogs, many samples throughout the Indian Ocean dataset were linked to modern analogs from various regions with diverse environmental characteristics. For example, a single site 763 sample at 3.05 Ma returned modern analogs of 0.13 SCD from both the tropical central Indian Ocean (27.5 °C) and the high-latitude south Atlantic Ocean (4.4 °C). Both modern samples are technically good analogs, but it is clear that temperature is not the common factor.

Future studies will focus on these non-analog assemblages, considering the degree of dissolution, the possibility of a non-analog Piacenzian environment, and the assumption of stationarity—the notion that ecological tolerances do not change with time. The assumption of stationarity appears to be reasonable: both techniques, for example, have been used to estimate SST in the mid-Piacenzian Atlantic and Pacific Oceans with much success (for example, Dowsett and others, 2009). While temperature is the single strongest factor in determining the relative composition of modern and most fossil foraminiferal assemblages, other factors such as surface productivity have been shown to have a strong effect (for example, Robinson and others, 2008) and may be influencing these Indian Ocean assemblages. Finally, a mixed layer environment of the past that does not exist today, with warmer surface temperatures or enhanced seasonal salinity stratification, for example, could explain the non-analog assemblages.

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