Global calibration of *Gephyrocapsa* coccolith abundance in Holocene sediments for paleotemperature assessment

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[1] A global sea surface temperature calibration based on the relative abundance of different morphotypes within the coccolithophore genus *Gephyrocapsa* in Holocene deep-sea sediments is presented. There is evidence suggesting that absolute sea surface temperature for a given location can be calculated from the relative abundance of *Gephyrocapsa* morphotypes in sediment samples, with a standard error comparable to temperature estimates derived from other temperature proxies such as planktic foraminifera transfer functions. A total of 110 Holocene sediment samples were selected from the Pacific, Indian, and Atlantic Oceans covering a mean sea surface temperature gradient from 13.6° to 29.3°C. Standard multiple linear regression analyses were applied to this data set, linking the relative abundance of *Gephyrocapsa* morphotypes to sea surface temperature. The best model revealed an r^2 of 0.83 with a standard residual error of 1.78°C for the estimation of mean sea surface temperature. This new proxy provides a unique opportunity for the reconstruction of paleotemperatures with a very small amount of sample material due to the minute size of coccoliths, permitting examination of thinly laminated sediments (e.g., a pinhead of material from laminated sediments for the reconstruction of annual sea surface temperature variations). Such fine-scale resolution is currently not possible with any other proxy. Application of this new paleotemperature proxy may allow new paleoenvironmental interpretations in the late Quaternary period and discrepancies between the different currently used paleotemperature proxies might be resolved. **INDEX TERMS:** 3022 Marine Geology and Geophysics: Marine sediments—processes and transport; 3030 Marine Geology and Geophysics: Micropaleontology; 3094 Marine Geology and Geophysics: Instruments and techniques; 4267 Oceanography: General: Paleoclimatology; 4294 Oceanography: General: Instruments and techniques; **KEYWORDS:** coccolithophores, temperature proxy, morphometry, Holocene, *Gephyrocapsa*

1. Introduction

[2] Abundance and assemblage composition of microplankton, together with their chemical and stable isotopic composition, have been among the most successful methods in paleoceanography and paleoclimatology [CLIMAP Project Members, 1976, 1981; Mix *et al.*, 2000, and references therein]. One of the most frequently applied techniques for reconstruction of paleotemperature is a statistical transfer function using the relative abundance of microplankton such as planktic foraminifera in sediment samples [Imbrie and Kipp, 1971; Molfino *et al.*, 1982; Pisias *et al.*, 1997]. This technique was successfully used for reconstruction of the sea surface temperatures during the last glacial maximum [CLIMAP, 1981]. However, in recent years there have been some doubts concerning the paleotemperature estimates of the CLIMAP project, especially at low latitudes [Rind and Peteet, 1985; Mix *et al.*, 2001, and references therein]. Therefore new approaches and proxies were developed and tested [Prah and Wakeham, 1987; Nürnberg *et al.*, 1996; Rickaby and Elderfield,

1999; Stoll and Schrag, 2000; Malmgren *et al.*, 2001]. One of these proxies uses alkenones, a biogeochemical component in marine sediments, for paleotemperature estimates [Prah and Wakeham, 1987]. In the modern ocean, alkenones are assumed to be produced mainly by the haptophyte species *Emiliania huxleyi* and *Gephyrocapsa oceanica* [Volkman *et al.*, 1980; Marlowe *et al.*, 1984; Volkman *et al.*, 1995]. However, there are uncertainties concerning the temperature calibration of alkenones, because of discrepancies between temperature estimates derived from *E. huxleyi* and *G. oceanica* strains grown under controlled laboratory conditions in culture experiments and those calculated from a global temperature calibration using core tops [Müller *et al.*, 1998; Volkman, 2000, and references therein].

[3] The assemblage composition of calcareous marine phytoplankton has not been widely and successfully applied for paleotemperature estimates, although the assemblage composition is closely related to environmental conditions [McIntyre *et al.*, 1970; Molfino *et al.*, 1982]. However, relative abundance changes of the species *Florisphaera profunda* have been used successfully to reconstruct the paleoproductivity in the Indian and Pacific Ocean during the Pleistocene [Beaufort *et al.*, 2001].

[4] The application of relative abundance changes of coccoliths for paleotemperature reconstruction has failed mainly due to the rapid evolution of single taxa [Roche *et al.*, 1975; Geitzenauer *et al.*, 1976], the dominance of single species, e.g., *E. huxleyi* [Thierstein *et al.*, 1977], and the insufficient knowledge of taxonomic complexity of species such as in the genus *Gephyrocapsa* [Bollmann, 1997; Bollmann *et al.*, 1998]. In this genus more morphotypes (most likely species) are extant than previously thought and they all are closely correlated with sea surface temperature and fertility patterns [Bollmann, 1997]. In fact, temperature preferences of single *Gephyrocapsa* species have already been used for qualitative temperature reconstructions [Weaver and Pujol, 1988; Takahashi and Okada, 2000].

[5] The present study evaluates several multivariate regression models for the prediction of sea surface temperature using the intragenetic relative abundance of *Gephyrocapsa* morphotypes in Holocene sediments. This new technique is a valuable aid in a multiproxy approach for past temperature reconstruction, where there are uncertainties concerning temperature estimates obtained with other methods. The approach provides a unique opportunity to reconstruct the sea surface temperature, e.g., from laminated sediments because only a tiny amount of sediment is needed.

2. Materials and Methods

[6] A total of 110 Holocene sediment samples were selected from the Pacific, Indian and Atlantic Oceans. Included in these are measurements of 66 samples published by Bollmann [1997]. In each ocean basin the samples range from high to low latitudes and from areas of high to low primary production (Figure 1a) covering a temperature gradient from 13.6° to 29.3°C and a fertility gradient of 0.045 to 1.2 µg chlorophyll/L (Figure 2). All data and related sample information are available electronically.¹

2.1. Sample Preparation

[7] All samples were prepared as follows: a small amount of sediment was suspended in alcohol and disaggregated by immersion in an ultrasonic bath. Subsequently, the suspension was sprayed onto a cover slide using an air gun [Bollmann *et al.*, 1999]. The cover slide was mounted on an aluminum stub and sputtered with gold for subsequent morphometric analyses of *Gephyrocapsa* coccoliths in a Hitachi S2300 scanning electron microscope (SEM) equipped with a slow scan digitizing unit (ADDA II, SIS).

2.2. Morphometry and Abundances of *Gephyrocapsa* Morphotypes

[8] All morphometric measurements (length and bridge angle of coccoliths) and the subsequent data treatment were

conducted following the procedures described by Bollmann [1997] (Figure 1b). The informal nomenclature of Bollmann [1997] was used to define different morphotypes of *Gephyrocapsa* coccoliths (Figure 1b): *Gephyrocapsa* transitional (GT), *Gephyrocapsa* oligotroph (GO), *Gephyrocapsa* cold (GC), *Gephyrocapsa* equatorial (GE), *Gephyrocapsa* larger (GL) and *Gephyrocapsa* minute (GM). The relative abundance of these six different morphotypes within the *Gephyrocapsa* complex were determined by subdividing each assemblage using the morphological boundary values between the six associations as published by Bollmann [1997] (Figure 1c).

[9] Because of inherent technical uncertainties when a SEM is used for geometric measurements (for details, see ASTM Committee E-4 [1993]) the geometry and accuracy of size measurements done in this study were controlled regularly by measuring about 30 calibration spheres with a diameter of 2 µm before and after a measurement campaign. All measurements with an apparent size offset were corrected. The comparison between measurements of the identical calibration spheres of a given diameter (1.98 µm ± 0.1 µm standard error) done by Bollmann [1997], Bollmann *et al.* [1998], and this study revealed that all measurements reported by Bollmann [1997] and Bollmann *et al.* [1998] are about 6.5% too small. The average diameter of all calibration spheres measured by Bollmann [1997] and Bollmann *et al.* [1998] is about 1.85 µm instead of 1.98 µm (J. Bollmann, unpublished data, 2002). This negative size offset was assumed to be negligible as the measurements varied within the given statistical standard deviation of ±0.1 µm for this type of calibration sphere and therefore the measurements have not been corrected for the apparent size offset by Bollmann [1997] and Bollmann *et al.* [1998]. However, in this study all measurements and the resulting morphological boundary values published by Bollmann [1997] were adjusted by a factor of 1.065 in order to avoid a biased sample set.

2.3. Environmental Data and Statistics

[10] All seasonal and annual mean sea surface temperatures (SST) as well as the chlorophyll concentrations (as a measure of the fertility) for all sample locations were taken from the World Ocean Atlas 1998 [Levitus *et al.*, 1998].

[11] Multiple regression analyses were applied linking the relative abundance of *Gephyrocapsa* morphotypes to sea surface temperatures. This method extends the simple regression analysis that relates y (e.g., SST) to x (e.g., relative proportion of a *Gephyrocapsa* morphotype) (i.e., $y = a + m \cdot x$) to include several predictor variables (e.g., $x_1, x_2, x_3, \dots, x_n$; i.e. $y = a + m_1 \cdot x_1 + m_2 \cdot x_2 + m_3 \cdot x_3 + \dots, m_n \cdot x_n$). Multiple regression models describe therefore the linear relationship between a response variable (e.g., SST) and several predictor variables (in our case the relative proportion of six *Gephyrocapsa* morphotypes). In order to obtain models with significant predicting variables (with a significant probability, P values < 0.05), stepwise multiple regression analyses versus sea surface temperatures were performed. In a stepwise multiple regression analysis, an automatic predictor variable selection procedure is used to find the best set of predictor variables (relative proportion of

¹ Supporting data and data tables are available via Web browser or via Anonymous FTP from <ftp://kosmos.agu.org>, directory "append" (Username = "anonymous", Password = "guest"); subdirectories in the ftp site are arranged by paper number. Information on searching and submitting electronic supplements is found at http://www.agu.org/pubs/esupp_about.html. They are also available electronically from the World Data Center-A for Paleoclimatology, NOAA/NGDC, 325 Broadway, Boulder, CO 80303, USA (e-mail: paleo@ngdc.noaa.gov; URL: <http://www.ngdc.noaa.gov/paleo/paleo.html>).

Figure 2. (a) Sample frequency with reference to mean sea surface temperature. (b) Sample distribution with respect to chlorophyll concentration and mean SST.

a *Gephyrocapsa* morphotype) for a regression model. In this analysis, a so-called forward selection procedure of predictor variables alternates with a so-called backward elimination procedure of predictor variables. For each predictor variable, an F statistic is calculated that reflects the contribution of the predictor variable to explaining the behavior of the response variable. The forward selection procedure begins with no predictors in the regression equation and then the predictor variable with the highest significance for the model enters the model first. The rest of the variables are entered into the regression model depending on the contribution of each predictor to the model.

[12] The backward elimination procedure is a modification of the forward selection technique. For each variable currently in the model, an F statistic is calculated. The variable with the lowest value of the F statistic is removed if the F statistic is not significant. If the F statistic for all variables is significant, then no variables are removed from the equation. At this point, the forward selection procedure starts again with the current model. If the forward selection procedure fails to add variables to the model, and the backward elimination procedure fails to remove variables from the equation, then the stepwise procedure stops and is considered to have produced the

Figure 3. Results of the best multiple regression model for mean SST. (a) Observed versus estimated mean SST. (b) Estimated versus residual mean SST.

Figure 4. Results of the multiple regression model for spring SST. (a) Observed versus estimated spring SST. (b) Estimated versus residual spring SST.

“best” model for explaining/predicting the SST (for details see, Kleinbaum *et al.* [1988]). All statistical analyses were performed using the statistics package S-Plus version 2000.

3. Results

[13] Standard stepwise linear multiple regression analysis was applied to the Holocene data set, linking the relative

abundance of *Gephyrocapsa* morphotypes to sea surface temperatures (T_{mean} , T_{max} , T_{min} , T_{spring} , T_{summer} , T_{fall} , T_{winter}). The results indicate (1) that the temperature variability spanned by the Holocene data set (13.6°–29.3°C) can be described rather accurately by the relative abundance variability of *Gephyrocapsa* morphotypes in Holocene sediments (Figures 3, 4, and 5 and Table 1) and (2) that the following three out of six *Gephyrocapsa* morphotypes reported by Bollmann [1997], explain most of the variance

Figure 5. Results of the multiple regression model for fall SST. (a) Observed versus estimated fall SST. (b) Estimated versus residual fall SST.

Table 1. Regression Models^a

	Value	Std. Error	t value	Pr(> t)
<i>Linear Model Mean SST^b</i>				
Coefficients				
(Intercept)	19.4336	0.6976	27.8573	0
%GE	0.1161	0.0119	9.7842	0
%GC	-0.056	0.0118	-4.7587	0
%GO	0.0806	0.0131	6.1595	0
Residuals ^c				
Minimum	-3.449°C			
1.Q	-1.434°C			
Median	-0.1181°C			
3.Q	1.255°C			
Maximum	3.868°C			
<i>Linear Model Spring SST^d</i>				
Coefficients				
(Intercept)	18.6467	0.8052	23.1568	0
%GE	0.1298	0.0137	9.4792	0
%GO	0.0942	0.0151	6.2385	0
%GC	-0.054	0.0136	-3.9703	0.0001
Residuals ^e				
Minimum	-5.317°C			
1.Q	-1.365°C			
Median	-0.1695°C			
3.Q	1.438°C			
Maximum	4.805°C			
<i>Linear Model Fall SST^f</i>				
Coefficients				
(Intercept)	20.1941	0.778	25.9571	0
%GE	0.1074	0.0132	8.1219	0
%GO	0.0691	0.0146	4.7376	0
%GC	-0.0666	0.0131	-5.0735	0
Residuals ^g				
Minimum	-4.125°C			
1.Q	-1.325°C			
Median	0.09221°C			
3.Q	1.186°C			
Maximum	4.379°C			
<i>Linear Model Winter SST^h</i>				
Coefficients				
(Intercept)	18.4379	1.1141	16.5491	0
%GE	0.1249	0.0189	6.5909	0
%GO	0.1043	0.0209	4.9908	0
%GC	-0.0519	0.0188	-2.7607	0.0068
Residuals ⁱ				
Minimum	-6.663°C			
1.Q	-1.943°C			
Median	-0.1416°C			
3.Q	1.842°C			
Maximum	6.602°C			
<i>Linear Model Summer SST^j</i>				
Coefficients				
(Intercept)	20.3491	1.0693	19.0295	0
%GE	0.1017	0.0182	5.5951	0
%GO	0.0559	0.0201	2.7871	0.0063
%GC	-0.0496	0.018	-2.7504	0.007
Residuals ^k				
Minimum	-6.466°C			
1.Q	-1.184°C			
Median	0.2852°C			
3.Q	1.519°C			
Maximum	6.253°C			
<i>Linear Model Maximum SST^l</i>				
Coefficients				
(Intercept)	21.89	0.6995	31.2942	0
%GE	0.0946	0.0119	7.9537	0
%GC	-0.0468	0.0118	-3.9622	0.0001
%GO	0.0685	0.0131	5.2223	0
Residuals ^m				
Minimum	-3.792°C			
1.Q	-1.252°C			
Median	-0.02464°C			
3.Q	1.187°C			
Maximum	4.475°C			

Table 1. (continued)

	Value	Std. Error	t value	Pr(> t)
<i>Linear Model Minimum SSTⁿ</i>				
Coefficients				
(Intercept)	16.9197	0.7909	21.3927	0
%GE	0.1365	0.0134	10.1503	0
%GC	-0.0551	0.0133	-4.126	0.0001
%GO	0.0903	0.0148	6.0911	0
Residuals ^o				
Minimum	-5.272°C			
1.Q	-1.304°C			
Median	0.06445°C			
3.Q	1.525°C			
Maximum	4.131°C			
<i>Linear Model Mean SST (Reduced by 11 Samples)^p</i>				
Coefficients				
(Intercept)	18.7295	0.6142	30.4961	0
%GE	0.1211	0.0101	12.0076	0
%GC	-0.0587	0.0105	-5.6141	0
%GO	0.1036	0.012	8.6421	0
Residuals ^q				
Minimum	-2.962°C			
1.Q	-1.128°C			
Median	-0.04538°C			
3.Q	1.079°C			
Maximum	3.021°C			

^a Multiple R-Squared represents the proportion of variance in the observations explained by the model. F statistic is F statistic to test the null hypothesis which assumes that the true coefficients are all 0. If the critical value of F at confidence level of 0.01 (99.5%) is larger than 4.5, this is the minimum F value for the rejection of the null hypothesis in a model with 3 variables and 120 degrees of freedom, the Null hypothesis can be rejected; p value is probability value for the test. Note that the null hypothesis can be rejected for all models presented and that the data suggest that all models are significant. Std. Error is standard error of the coefficients; t value is t statistics testing whether the coefficient is significantly different from zero; Pr(>|t|) are p values for each such t test. 1.Q is first quartile; 3. Q is third quartile. The residual standard error is the estimated standard error of the residuals.

^b MeanSSTPRED = 19.4336 + (0.1161 * %GE) + (-0.0560 * %GC) + (0.0806 * %GO). Multiple R-Squared is 0.8325. F statistic is 175.6 on 3 and 106 degrees of freedom; the p-value is 0.

^c Residual standard error is 1.787°C on 106 degrees of freedom.

^d SpringSSTPRED = 18.6467 + (0.1298 * %GE) + (-0.0540 * %GC) + (0.0942 * %GO). Multiple R-Squared is 0.8121. F statistic is 152.7 on 3 and 106 degrees of freedom; the p value is 0.

^e Residual standard error is 2.063°C on 106 degrees of freedom.

^f FallSSTPRED = 20.1941 + (0.1074 * %GE) + (-0.0666 * %GC) + (0.0691 * %GO). Multiple R-Squared is 0.8001. F statistic is 141.4 on 3 and 106 degrees of freedom; the p value is 0.

^g Residual standard error is 1.993°C on 106 degrees of freedom.

^h WinterSSTPRED = 18.4379 + (0.1249 * %GE) + (-0.0519 * %GC) + (0.1043 * %GO). Multiple R-Squared is 0.6856. F statistic is 77.03 on 3 and 106 degrees of freedom; the p value is 0.

ⁱ Residual standard error is 2.854°C on 106 degrees of freedom.

^j SummerSSTPRED = 20.3491 + (0.1017 * %GE) + (-0.0496 * %GC) + (0.0559 * %GO). Multiple R-Squared is 0.61. F statistic is 55.26 on 3 and 106 degrees of freedom; the p value is 0.

^k Residual standard error is 2.739°C on 106 degrees of freedom.

^l MaximumSSTPRED = 21.8900 + (0.0946 * %GE) + (-0.0468 * %GC) + (0.0685 * %GO). Multiple R-Squared is 0.7711. F statistic is 119 on 3 and 106 degrees of freedom; the p value is 0.

^m Residual standard error is 1.792°C on 106 degrees of freedom.

ⁿ MinimumSSTPRED = 16.9197 + (0.1365 * %GE) + (-0.0551 * %GC) + (0.0903 * %GO). Multiple R-Squared is 0.8265. F statistic is 168.4 on 3 and 106 degrees of freedom; the p value is 0.

^o Residual standard error is 2.026°C on 106 degrees of freedom.

^p MeanSSTPRED = 18.7295 + (0.1211 * %GE) + (-0.0587 * %GC) + (0.1036 * %GO). Multiple R-Squared is 0.8942. F statistic is 267.6 on 3 and 95 degrees of freedom; the p value is 0.

^q Residual standard error: 1.474°C on 95 degrees of freedom.

Figure 6. Relative proportions of the six *Gephyrocapsa* morphotypes in each sample versus mean SST.

within the models: *Gephyrocapsa* cold (GC), *Gephyrocapsa* oligotrophic (GO) and *Gephyrocapsa* equatorial (GE). Morphotypes *Gephyrocapsa* transitional (GT), *Gephyrocapsa* larger (GL) and *Gephyrocapsa* minute (GM) were found to be of minor importance in the temperature regression models.

[14] The best multiple regression model yielded $R^2 = 0.83$, with a standard residual error of 1.78°C for mean sea surface temperature. Values with an $R^2 = 0.81$ and a standard residual error of 2.0°C , and $R^2 = 0.80$ and a standard residual error of 2.0°C , respectively, apply to the spring and fall sea surface temperature. The models for minimum, maximum and all other seasonal temperatures revealed an R^2 ranging from 0.61 to 0.82 with standard errors of 1.8° to 2.9°C (Table 1).

[15] All models, however, are restricted to a temperature range of 14° – 29.4°C because below a mean sea surface temperature of 14°C , only the *Gephyrocapsa* cold morphotype occurs. Application of the transfer function to two plankton filter samples with an in situ temperature of 28.6°C (equatorial Pacific) and 14.8°C (North Atlantic), respectively, revealed temperature estimates of 28.75° and 16.18°C , respectively.

4. Discussion

[16] A successful application of transfer function techniques to the reconstruction of paleoenvironments requires that a few crucial conditions be met [Imbrie and Kipp,

1971]. These are (1) a close correlation of species abundances in Holocene microfossil assemblages with measured oceanographic parameters, (2) no or minimal alteration of fossil assemblages by differential dissolution, winnowing or reworking, (3) even sample distribution along the environmental gradients to be re-estimated, (4) no evolutionary adaptation to other environmental preferences occurred, and (5) nonanalogue assemblage compositions are not included or do not occur.

[17] These conditions are met in our data set as follows. (1) The relative abundance of the morphotypes GC, GO, and GE closely follow mean sea surface temperature as shown in Figure 6. Furthermore, there is no regional bias within the data as already shown by Bollmann [1997] and supported by the accurate in situ temperature estimates of the two plankton samples from the North Atlantic and the equatorial Pacific. (2) Carbonate dissolution has a negligible effect on size and bridge angle determination of *Gephyrocapsa* coccoliths [Bollmann et al., 1998], and it appears that all *Gephyrocapsa* morphotypes have more or less the same preservation potential. (3) Sample distribution with respect to temperature is not skewed in the present data set (Figure 2a). (4) Evolutionary adaptation through time is the most likely cause of erroneous results in transfer functions based on the relative abundance of organisms. All models suffer from this potential source of error because evolutionary adaptation to different environmental conditions takes place in every group of organisms.

[18] So far there is no general agreement concerning the taxonomy and phylogeny of *Gephyrocapsa* species. From the preliminary results of Bollmann *et al.* [1998] concerning the phylogeny of *Gephyrocapsa*, all Holocene morphotypes have been present in the last 250 ka. Thus the *Gephyrocapsa* transfer function may be applicable to sediments younger than 250 ka. First results from a study off North-west Africa reveal that the temperature estimates obtained with the *Gephyrocapsa* transfer function are in good agreement with alkenone derived temperatures for the last 28 ka (J. Henderiks and J. Bollmann, unpublished data, 2002) indicating that the drop in mean sea surface temperature in this area was around 2° to 3°C during the Last Glacial Maximum, and not 4° to 7°C as proposed by CLIMAP Project Members [1981] (for details, see Henderiks and Bollmann [2001]).

[19] The standard error of 1.78°C is comparable to that of foraminifera transfer functions [Imbrie and Kipp, 1971]. However, a standard error of 1.5°C or smaller would be desirable and would be comparable to temperature estimates derived from the global alkenone calibration [Müller *et al.*, 1998]. Currently this standard error can only be obtained by exclusion of samples with the most erroneous temperature estimates from the data set. By stepwise elimination of such outlier samples, in total 11 samples, a model with an $R^2 = 0.89$ and a standard error of 1.47°C is reached (Table 1). However, there is currently no evidence, such as reworking or age anomalies, to justify the exclusion of these samples from the calibration data set.

[20] Because of inherent methodological difficulties, necessary assumptions and possible nonanalogue situations in the past, it has become common practice to apply independent and complementary techniques for paleoenvironmental reconstructions, the so-called multiproxy approach [see Mix *et al.*, 2000]. We now can add one more to these based on *Gephyrocapsa* morphology.

5. Conclusions

[21] The *Gephyrocapsa* temperature transfer function has great potential for the reconstruction of paleotemperatures in the temperature range from 14° to 29.4°C. The standard error of 1.78°C is comparable to that of foraminifera transfer functions [Imbrie and Kipp, 1971]. However, this technique opens new opportunities for the reconstruction of paleotemperatures because only a very small amount of sample material is required, for example as little as 0.5 mg of material from laminated sediments.

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