Coccolithophores as palaeoecological indicators for shifts of the ITCZ in the Cariaco Basin during the late Quaternary

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ABSTRACT: Coccoliths were studied from the ODP Hole 1002C and core PL07-39PC in the Cariaco Basin. Increases in Emiliania huxleyi are synchronous with decreases of Gephyrocapsa oceanica and vice versa. A new index (GEX) based on the relative abundances of these two taxa is proposed, and correlates with various other proxies. It is shown that GEX can serve as upwelling proxy. This confirms that the Intertropical Convergence Zone shifted north during the Bølling/Allerød, south during the Younger Dryas and back north during the Preboreal. The upwelling proxy shows few discrepancies with the terrigenous record. Copyright © 2008 John Wiley & Sons, Ltd.

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KEYWORDS: Cariaco; coccoliths; Quaternary; dissolution; GEX.

Introduction

The equatorial Atlantic plays a key role in global climate changes during the Quaternary. Evidence is increasing that large and rapid climate oscillations occurred at suborbital and millennial frequencies in the North Atlantic during the last glacial (Heinrich events and Dansgaard/Oeschger cycles) (Bond et al., 1992, 1997; Dansgaard et al., 1993). Apparently, these are not restricted to the northern higher latitudes but have a global signature, which is also prominent in the Caribbean Sea (Peterson et al., 2000; Schmidt et al., 2004). The mechanisms for these pronounced changes in the atmosphere–ocean system are still a matter of debate, partly because of the scarceness of high-resolution data from the tropics and the southern hemisphere (Vidal et al., 1999; Vink et al., 2001). These changes in the climate system are well reflected in high-resolution productivity data (Peterson et al., 2000; Vink et al., 2001), mainly from shelf areas where 10–15% of the global marine primary production takes place (Muller-Karger et al., 2005). Pronounced fluctuations in production are more likely to occur within these borderlands. The Cariaco Basin, located on the Venezuelan margin, is characterised by high productivity, which has caused the basin to become anoxic. In this respect, the basin offers an important opportunity to study changes of productivity.

Coccolithophores are a major plankton group and play an important role in biogeochemical cycles and climate. However, these unicellular algae are not so commonly used for palaeoceanographical and palaeoclimatological studies. This may be partly due to the cosmopolitan range and ubiquitous occurrence of only a few dominant species. Nevertheless, biogeographical distribution patterns of coccoliths in surface sediments reflect the distribution of living coccolithophore species in the overlying water masses (Baumann et al., 1999). Major ecological factors explaining the spatial and temporal distributions of coccolithophores are discussed in Baumann et al. (2005) and Jordan (2002). The sinking flux of coccolithophores constitutes about 60% of the total burial flux of CaCO3 to the world’s sediments, with a regional variability of 20–86% (Honjo, 1996), which makes them an ideal tool for high-resolution productivity study.

Coccolithophores are a major constituent of the phytoplankton blooms which occur during the upwelling season in the Cariaco Basin. This study reports variations in coccolith taxa preserved in sediments of Cariaco Basin and their use for the interpretation of climate and ocean variability in the southern Caribbean region during the latest Quaternary on a millennial timescale, through a high-resolution analysis of quantitative coccolith fluctuations in the Cariaco Basin. Using a multi-proxy analysis with new data from a geochemical analysis (total organic carbon (TOC) and carbonate), a Pteropod abundance...
ratio and a palynological analysis, combined with earlier published data (Mg/Ca, alkenones, Mo/Al, X-ray fluorescence), a robust framework for the elucidation of the variations in the coccolith record, is presented.

**Study area and background**

The Cariaco Basin is a small east–west trending Quaternary pull-apart basin on the continental shelf, north of Venezuela (Fig. 1). It is composed of two sub-basins, separated by a 950 m deep saddle. The western basin has a depth up to 1400 m, while the eastern basin has a maximum depth of 1370 m. The basin is isolated in the north from the inlet of deep water from the Caribbean by a series of sills which form the Tortuga Bank; the deepest connections between the basin and the open Caribbean are at a depth of 146 m, in the north-west. The surrounding topography prohibits inlet of deep water from the Caribbean, causing a 100 a residence time of the bottom waters (Deuser, 1973). The high oxygen demands, created by upwelling-induced surface productivity, and a strong pycnocline which limits vertical exchange, leads to the present-day anoxic and sulphidic conditions below a depth of 300 m (Richards, 1975; Peterson et al., 1991). The almost complete lack of bioturbation leads to a very complete sedimentary record.

The most important surface waters entering the Caribbean are the North Brazil Current (NBC) and the North Equatorial Current (NEC). These branch off around the Lesser Antilles and flow into the Caribbean Basin to form the Caribbean Current. The two upper water masses are the Caribbean Surface Water (CSW) and the Subtropical Under Water (SUW). The oligotrophic CSW (0–80 m) originates from the NEC and NBC with significant input of low-salinity waters of the Amazon and Orinoco rivers in October–November. The eutrophic SUW (at a depth of 80–120 m), comes from the centre of the North Atlantic (the surface waters of the North Atlantic Gyre) and enters the Caribbean between the Lesser Antilles and the Windward Passage between Cuba and Jamaica (Wust, 1964; Nyberg et al., 2002). The SUW forms the permanent thermocline and/or nutricline of the Caribbean. The surface water of the Caribbean is generally characterised by low primary productivity except in coastal regions, for example off the Venezuelan coast, where due to upwelling this SUW is shoaling and causes higher productivity (Muller-Karger and Aparicio-Castro, 1994).

The region is influenced by migrations of the Intertropical Convergence Zone (ITCZ), which causes seasonal variations in the strength of the north-east trade winds (Muller-Karger and Aparicio-Castro, 1994). During winter and early spring (January–March), the ITCZ is at its southernmost position and strong trade winds blow along the coast of Venezuela, causing upwelling of nutrient-rich water. The phytoplankton exploits this resource and in January and February primary production rates and carbonate and opal fluxes are at a maximum (Peterson et al., 1991). During this period, diatoms dominate the phytoplankton population (Ferraz-Reyes, 1983). Beginning from about June or July, when the ITCZ migrates north to a position near the Venezuelan coast, the trade winds weaken markedly and primary production rates fall to a minimum (Muller-Karger et al., 2004). As the upwelling subsides, the northward migration of the ITCZ brings its associated rainbelt above the Cariaco Basin, and increases fluvial discharge from rivers which affect the southern Caribbean. No large rivers currently discharge into the basin, but in former times fluvial input was more important (Muller-Karger et al., 1989). During this season, the production is dominated by cyanobacteria, dinoflagellates (Ferraz-Reyes, 1983) and also haptophytes (Goni et al., 2003).

The interglacial basin sediments are laminated and reflect migrations of the ITCZ as the high annual sediment flux (20–

![Figure 1](image_url)
100 cm ka\(^{-1}\)) forms alternating light and dark laminae. The light laminae are mainly composed of diatoms; they reflect high winter–spring production. The microorganisms appear grouped in aggregates, most likely faecal pellets, surrounded by biogenic silica. The dark laminae have a higher clay and terrigenous material composition, with mainly quartz and feldspars, and this reflects deposition during the summer–autumn rainy season in combination with reduced productivity. Microorganisms in these laminae are also grouped in aggregates.

Materials and methods

ODP Site 1002 (10° 42.37' N, 65° 10.18' W) is located on the western flank of the central saddle of the Cariaco Basin, at a depth of 893 m (Fig. 1). The saddle was chosen because the varves in the sub-basins tend to be disrupted by microturbidites. Shipboard Scientific Party (1997) gives the detailed sediment core location and description.

Core PL07-39PC (10° 42.00' N, 64° 56.50' W) was recovered from a water depth of 790 m on the eastern side of the central saddle that bisects the basin (Fig. 1), and is described in Lin et al. (1997).

Stratigraphy

Hole 1002D is well dated with 65 accelerator mass spectrometry (AMS) \(^{14}\)C dates on planktonic foraminifera, over the studied interval, and was fine-tuned to GISP II \(^{18}\)O by matching inflection points and interpolating between them (Hughen et al., 2004). Hole 1002C was then aligned with hole 1002D by visually matching magnetic susceptibility records provided by Shipboard Scientific Party (1997). The studied core sections range in age from Late Pleistocene to the earliest Holocene, covering the Last Glacial Maximum (LGM), Heinrich event 1, the Bölling–Alleröd Warm Period (BA), the Younger Dryas (YD) and the Holocene.

Core PL07-39PC is dated with 29 AMS \(^{14}\)C dates on planktonic foraminifera, and has a detailed oxygen isotope record and greyscale correlations (Hughen et al., 1996a,b; Lin et al., 1997).

Sedimentation rates in both cores were calculated by taking the moving average of the two slopes immediately next to the point in the age–depth diagram (Fig. 2) and range from about 32 to 170 cm ka\(^{-1}\). The slower rates are associated with deposition of the faintly laminated upper portion of the core, the highest ones with Heinrich 1 and YD. Mass accumulation rates in hole 1002C were calculated using dry bulk density measurements based on GRAPE density measurements (Shipboard Scientific Party, 1997) in PL07-39PC (Lynn, 1998). There could be two reasons for discrepancies between both cores: one of the cores had been stretched/compressed on certain intervals due to coring, or there had been varying inputs of productivity or terrigenous input (both cores are at different sides of the saddle).

Mass accumulation rates (MAR) are much higher during glacial periods and the YD than interglacial periods. MAR during the BA are clearly lower than glacial MAR.
Quantification of coccoliths and coccolith carbonate

Samples were taken at 10 cm intervals. Given the range of sedimentation rates, this sampling interval yields a temporal sampling resolution of between about 100 and 300 a. The method of Okada (2000) was used for preparation of the studied 95 samples from hole 1002C. 400 nanofossils were counted under a Jeol 6400 scanning electron microscope at a magnification of 2700×. Absolute abundances were calculated using the formula of Lototskaya (1999):

\[ N = \frac{V_1 + S_f \times N'}{V_2 + n_s \times S_f \times m_{\text{BDB}}} \]

where \( N \) = absolute abundances of coccoliths g\(^{-1}\) dry sediment; \( V_1 \) = volume of tap water used for filtering; \( S_f \) = effective filtration area; \( N' \) = number of counted coccoliths; \( V_2 \) = volume of the solution; \( n_s \) = number of counted square fields; \( S' \) = area of the field; \( m_{\text{BDB}} \) = weight of a bulk sediment sample (g). Coccolith accumulation rates can then be calculated as \( \text{cocAR} = R \times \text{DBD} + N \), with \( \text{cocAR} = \text{total coccolith accumulation rate} \) (coccolith cm\(^{-2}\)ka\(^{-1}\)); \( R \) = average sedimentation rate (cm ka\(^{-1}\)); \( \text{DBD} \) = dry bulk density (g cm\(^{-3}\)); and \( N \) = absolute abundances of coccoliths g\(^{-1}\) dry sediment (number g\(^{-1}\)).

The number of coccoliths was converted into coccolith carbonate content on the basis of mean estimates of coccolith masses (Young and Ziveri, 2000). Since the mass of coccolith species varies markedly, size calibrations are necessary (Baumann, 2004) and 50 measurements of the length of the most important taxa were taken as in Baumann et al. (2003). They were converted into mass estimates using the method of Young and Ziveri (2000) (Table 1).

For core PL07-39PC, samples were also taken at 10 cm intervals for this study. Initial sample preparation followed standard micropalaeontological techniques. Core samples were washed through a 63 \( \mu \)m sieve, saving 1 L of the <63 \( \mu \)m fraction. The <63 \( \mu \)m fraction was allowed to settle for 2 days or until the water was clear, then excess water was siphoned off. The last 50 mL was left to avoid disturbance of the settled fraction; this remaining water was evaporated off under a heat lamp. The dried fine fraction was then scraped out of the beaker and saved for analysis. Owing to the high proportion of clay material in these samples, coccolith concentration techniques were employed before the samples were counted. This procedure simplified the relative abundance counts but invalidated any later attempt at generating absolute abundance data from the same samples; consequently separate preparations were required to accommodate the absolute abundance study.

Total organic carbon and carbonate

TOC was measured by Rock Eval pyrolysis using a Rock Eval IV apparatus. Carbonate percentage was measured in hole 1002C.

Table 1  Lengths and masses of selected species

<table>
<thead>
<tr>
<th>Species</th>
<th>Length (( \mu )m)</th>
<th>Mass (( \mu )g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G. oceanica</td>
<td>4.78</td>
<td>15.41</td>
</tr>
<tr>
<td>E. huxleyi</td>
<td>3.08</td>
<td>1.61</td>
</tr>
<tr>
<td>C. leptoporus</td>
<td>7.90</td>
<td>109.72</td>
</tr>
<tr>
<td>F. profunda</td>
<td>4.12</td>
<td>8.54</td>
</tr>
<tr>
<td>H. carteri</td>
<td>7.41</td>
<td>59.82</td>
</tr>
<tr>
<td>U. sibogae</td>
<td>4.89</td>
<td>18.44</td>
</tr>
<tr>
<td>S. pulchra</td>
<td>5.33</td>
<td>13.00</td>
</tr>
<tr>
<td>Umbellosphaera spp.</td>
<td>6.16</td>
<td>10.36</td>
</tr>
</tbody>
</table>


Quantification of pteropods and pteropod ratio

After wet sieving at 63 \( \mu \)m, the sample was split multiple times, depending on the abundance of pteropods. The number of pteropods was calculated by multiplying by the splitting factor and dividing by dry sample weight. Pteropod abundance ratio was calculated by (\# pteropods g\(^{-1}\)) / (\# pteropods g\(^{-1}\) + # planktonic foraminifera g\(^{-1}\)).

Results

All raw data are included as supporting information to this paper.

Coccolith relative abundance data

The assemblages found in the area off Venezuela are typically tropical, dominated by placolith-bearing species such as *Emiliania huxleyi*, *Gephyrocapsa oceanica*, *Umbilicosphaera sibogae* and *Calciscus leptoporus* (Figs. 3 and 4). Thirty-nine nanofossil species were identified in core 1002C, but only two species reach relative abundances of more than 15% (5 dry sediment) *Gephyrocapsa oceanica* (16–92%) and *Emiliania huxleyi* (0–72%). Other important species are *Florisphaera profunda* (up to 15%), *Umbilicosphaera sibogae* (up to 12%), *Helicosphaera carteri* (up to 9%), *Calciscus leptoporus* (up to 7%), *Gladiolithus flabellatus* (up to 7%), small *Gephyrocapsa* (up to 7%) and *Acanthoica* spp. (up to 5%). Species with low relative abundances were *Reticulofenestra sessili* (up to 3%), *Syracosphaera pulchra* (up to 3%), *Rhabdosphaera clavigera* (2%), *Umbellosphaera* spp. (up to 2%), *Clypeosolenia* spp. (up to 2%), *Michaelarsenia* spp. (up to 2%), *Reticulofenestra parvala* (up to 1%), *Discosphaera tubifera* (up to 1%), *Hayaster perplexus* (up to 1%), *Algirosphaera robusta* (up to 1%), *Helicosphaera pavimentum* (less than 1%), *Gephyrocapsa caribbea* (less than 1%), *Ponto- sphaera* spp. (less than 1%), *Calcipappus rigidius* (less than 1%), *Syracolithus dalmaticus* (less than 1%), *Ceratolithus cristatus* (1%), *Emiliania huxleyi* and *Gephyrocapsa oceanica* are characterised by very rapid abundance changes in the investigated time interval. Increases in relative abundances of *Emiliania huxleyi* are synchronous with decreases of *Gephyrocapsa oceanica* and vice versa.

Coccoliths per gram of sediment and absolute abundance data (coccolith accumulation rates)

The number of coccoliths per gram of sediment range in 1002C from 3.2 × 10\(^8\) to 8 × 10\(^9\). Boeckel and Baumann (2004) studied the distribution in surface sediments of the southeastern South Atlantic Ocean and found total coccolith abundances using a manocalcimeter. Details of the methods are described in Aycard et al. (2008).
Figure 3. Relative abundances of coccoliths in core 1002C.
Figure 4  Relative abundances of coccoliths in core PL07-39PC
ranging from 0.2 to 39.9 coccoliths × 10^9 g^−1 sediment. Liths per gram of sediment calculated by Kinkel et al. (2000) from a core in the western equatorial Atlantic range between 10 × 10^9 and 40 × 10^9 liths m^−2 ka^−1. Our estimates fall well within these ranges.

Coccolith accumulation rates were calculated for each species and ranged from 18 × 10^9 to 49 × 10^10 liths cm^−2 ka^−1. Accumulation rates calculated by Kinkel et al. (2000) in a core in the Ceara Rise, western equatorial Atlantic, vary between 8.5 × 10^9 and 45 × 10^9 liths cm^−2 ka^−1. The Cariaco Basin thus has in general a greater contribution of coccoliths than the core of Kinkel et al. (2000). This can be expected, since the Cariaco Basin is considered to be a higher productivity area than the western equatorial Atlantic.

The accumulation rates can be converted to fluxes, which allows comparison to fluxes measured in sediment traps. Our fluxes correspond to 4.93 × 10^8 to 1.34 × 10^10 liths m^−2 d^−1. Current coccolith fluxes in the mid-equatorial Atlantic measure from 6.2 × 10^9 to 7.8 × 10^9 liths m^−2 d^−1 in the mid-equatorial Atlantic (Steinmetz, 1991). Haidar and Thierstein (2001) measured an average flux of 1.4 × 10^9 liths m^−2 d^−1 around Bermuda. Our calculated fluxes are within the same order of magnitude.

Coccolith carbonate

For core 1002C, the carbonate produced by coccolithophores was calculated using the mass estimates in Table 1 (Fig. 5). On average, 23% of the total carbonate in the sediment has been produced by coccolithophores over the last 21 ka, the remaining carbonate being attributed to foraminifers and pteropods. The highest percentage of coccolith carbonate was reached during the BA and Preboreal.

Baumann et al. (2003), using sediment traps in the South Atlantic region measured a contribution of coccolith carbonate on average 9.1% of the CaCO_3 fluxes. Boeckel and Baumann (2004) studied coccolith distribution in surface sediments of the southeastern South Atlantic Ocean; their mass estimations of the coccolith carbonate reveal coccoliths to be only minor contributors to the carbonate preserved in the surface sediments. The mean computed coccolith carbonate content is 17 wt%, equivalent to a mean contribution of 23% to the bulk carbonate. Our estimates are thus comparable.

We have to stress that different methodologies are used in the above-mentioned papers, which may cause problems of comparison of absolute quantification (Herrle and Bollmann, 2004). However, the comparison of general trends presents no problem.

TOC, carbonate and rain ratio

TOC increases during interglacial periods after the anoxic transition; extreme differences are much higher TOC in the BA and Preboreal, and a minimum TOC during the YD (Fig. 5). Carbonate percentage shows opposite fluctuations to TOC. The rain ratio (TOC/carbonate) is synchronous to TOC. The average organic carbon accumulation is 0.95 g cm^−2 ka^−1 during the Holocene (after 11.7 cal. ka BP), and 1.26 g cm^−2 ka^−1 before the Holocene. Goni et al. (2003) measured burial fluxes of about 1–1.2 g cm^−2 ka^−1 in a core on the eastern flank, an average comparable to measured fluxes in both core 1002C and PL07–39PC, and also similar to measurements in the deeper sediment traps (1–1.4 g cm^−2 ka^−1).

The average carbonate accumulation is 5.15 g CaCO_3 cm^−2 ka^−1 during the Holocene, and 9.409 g CaCO_3 cm^−2 ka^−1
before the Holocene. There is clearly a decrease in accumulation.

Goni et al. (2003) measured burial fluxes of about 3–4 g cm\(^{-2}\) ka\(^{-1}\) in a core on the eastern flank. However, our data do not resemble the fluxes measured in deeper sediment traps, only the fluxes in the shallow traps. Such a difference has been attributed to various causes; some uncertainty remains about the extent of loss of carbonate through the water column (Smoak et al., 2004).

Pteropod ratio

The pteropod ratio reaches a maximum during Heinrich event 1 and the YD and a minimum during the BA and Preboreal (Fig. 6).

Discussion

Below, the interpretation of the coccolith records will be discussed. This interpretation will be used to link this information to migrations of the ITCZ, leading to a palaeoclimatological reconstruction of the Cariaco Basin.

Variation between *Emiliania huxleyi* and *Gephyrocapsa oceanica*

First and foremost, the variations in relative and absolute abundances of *Emiliania huxleyi* and *Gephyrocapsa oceanica* require an explanation. These bloom-forming species are genetically closely related (Medlin et al., 1996; Fujiwara et al., 2001) and are thought to affect biogeochemical cycles of, in particular, CO\(_2\) (Tyrrell and Taylor, 1995; Rost and Riebesell, 2004), climate (dimethyl sulphide cloud cover; Malin and Steinke, 2004) and light-scattering albedo (Tyrrell, 1999).

We can express the signal from the two dominant coccolith taxa as GEX (*Gephyrocapsa oceanica*–*Emiliania huxleyi* index), as an analogue to the CEX of Dittert et al. (1999) (*Calcidiscus leptoporus*–*Emiliania huxleyi* dissolution index), and the CEX' (*Calcidiscus leptoporus*–*Emiliania huxleyi* + *Gephyrocapsa ericsonii* dissolution index) of Boeckel and Baumann (2004), which are analogue indices with different species.

\[
\text{GEX} = \frac{E.\ huxleyi\ %}{E.\ huxleyi\ % + G.\ oceanica\ %}
\]

\[
\text{CEX} = \frac{E.\ huxleyi\ %}{E.\ huxleyi\ % + C.\ leptoporus\ %}
\]

\[
\text{CEX'} = \frac{E.\ huxleyi + G.\ ericsonii\ %}{E.\ huxleyi + G.\ ericsonii\ % + C.\ leptoporus\ %}
\]
We will consider two complementary ways in which to explain variations between these two species: one invoking ecological changes and the other dissolution.

Ecology as interpretation

Changes between *E. huxleyi* and *G. oceanica*, as reflected by the GEX ratio, can be linked to changes between an upwelling-dominated ecosystem and a river-dominated ecosystem. These shifts correspond to an environment with more nutrients, higher SSS and lower SST and reduced water column stability and to an environment with fewer nutrients, lower SSS and higher SST and higher stratification. Each of these environments can be related to dominance of one of either taxon.

*E. huxleyi* is often linked with upwelling (Smayda, 1966; Berger, 1976; Stoll et al., 2007). Tyrrell and Merico (2004) postulated that *E. huxleyi* blooms right after the spring diatom bloom when surface irradiances are increasing, and silicate is the limiting factor. The fact that *E. huxleyi* is uninhibited by high light intensities may account for its success at outcompeting other species when it forms gigantic blooms. This same seasonal cycle could be occurring in the Cariaco Basin during the YD. Diatom blooms occur during the YD, as shown by thick diatom laminations (Peterson et al., 2000; Piper and Dean, 2002). The increase in the GEX ratio during the YD would thus reflect the increase in upwelling, due to the increases of *E. huxleyi*. Coccolith accumulation rates show the same trends and major inflection points as the GEX, and would also reflect upwelling conditions (compare Figs. 6 and 7).

On the other hand, increases in *G. oceanica* abundances can be related to less saline, warm water and possibly by river runoff. This has been acknowledged in other studies. According to Jordan and Winter (2000), who studied coccolith assemblages off the coast of Puerto Rico, a nearby region, there can be a relationship between abundances of Gephyrocapsa oceanica and inflow of shallow coastal waters. Also Kleijne et al. (1989), Zhang and Siesser (1986) and Knappertbusch (1993) mention blooming of *G. oceanica* at lower salinities than *E. huxleyi*. In the neritic Gulf of Panama it was also found to be the dominant species (Smayda, 1966; Throndsen, 1972). On the other hand, in the oligotrophic Caribbean, it has been only rarely observed (Throndsen, 1972). Weaver and Pujol (1988) mention this species as an indicator of warming and runoff for the Mediterranean. A multi-proxy approach of Arabian Sea sediments by Doose-Rolinski et al. (2001) also indicates the ratio between *G. oceanica* and *E. huxleyi* being indicative for warmer and fresher conditions related to higher monsoon activity.

Dissolution as interpretation

In contrast to well-preserved assemblages of planktonic foraminifera, often enriched in delicate forms, even the best-preserved recent coccolith assemblages in sediments contain only a small fraction of the taxa found in the water column and are generally dominated by dissolution-resistant taxa and, as such, coccoliths are sensitive indicators of the degree of dissolution (Thierstein, 1980; Roth and Coulbourn, 1982). Coccoliths, therefore, are sensitive indicators of the degree of dissolution in well-preserved assemblages, whereas planktonic foraminifera are sensitive indicators for more dissolved samples (Roth and Berger, 1975).

Carbonate dissolution will have a stronger effect on the delicate *E. huxleyi* than on *G. oceanica*, a fact acknowledged by other studies (e.g. Haidar and Thierstein, 2001). Therefore the GEX will decrease with increasing carbonate dissolution. Selective dissolution of coccolithophores is also reflected in other species such as *G. oceanica*, *C. leptoporus* and *H. carteri*, which are dissolution resistant, whereas *E. huxleyi* and umbelliform species are more delicate. Indeed, clear traces of dissolution are indicated by CEX, for example, around 14.2 ka, a period when *G. oceanica* clearly becomes dominant (Fig. 7). In our case, CEX is probably not that applicable since *Calcidiscus leptoporus* abundance is too low to leave a high enough imprint in the fossil record, except for rare occasions when the dissolution is very marked. As far as we can see, extended counting of *C. leptoporus* and *E. huxleyi* would reveal the same trends as GEX.

This process of dissolution would occur while the coccoliths are transported through the water column. Sediment trap studies in the Cariaco Basin show that major loss of organic carbon and carbonate occurs during transport through the water column. About 60–70% of the carbonate is currently lost in the upper 1000 m, according to Goni et al. (2003), and 71.5% according to Smoak et al. (2004). Another observation made during the coccolith counts was that in any given sample throughout the section coccoliths of every species seem to be present with very variable preservation, from pristine to very poorly preserved. This lends support to the idea that varying amounts of dissolution took place during the settling of coccoliths to the seafloor, and less on the seafloor itself, where one would expect a more homogeneous effect on the total assemblage. We therefore suggest syndepositional dissolution being the most important process. A possible process that would be occurring would be similar to what Klockner and Henrich (2006) propose for the Arabian Sea. Low trade wind activity would cause higher dissolved DIC/low pH anoxic conditions deeper in the basin, and would cause higher carbonate dissolution. High trade wind activity would result in deep winter mixing, and lower DIC/higher pH conditions deeper in the basin, favouring carbonate preservation. This can again be related to shift between environments (Fig. 9).

Multi-proxy approach

Different other proxies that have been produced on both cores by other workers show similar fluctuations to the GEX ratio (Figs 7 and 8). In this paragraph, we want to show that both productivity and preservation can be applied in the interpretation of these records.

The rain ratio, defined as TOC%/CaCO₃%, shows similar fluctuations to GEX in both cores (Figs. 7 and 8). The rain ratio has previously been considered to be indicative of dissolution (Emerson and Bender, 1981; Jahnke et al., 1994; Dittert et al., 1999). However, this rain ratio can also be related to productivity: higher upwelling rates would then result in higher carbonate production by foraminifera (and coccoliths) and lower input of river-related reducing organic matter. On the other hand, these periods with highest accumulations of carbonate are also the periods of lowest dissolution (Bonifay and Giresse, 1992), and this is precisely the case (compare Figs. 6 and 7).

We can also note that the aragonitic pteropod abundance index as calculated by Lin in core PLO7-39PC shows the same trends as our rain ratio and GEX (Fig. 8). These higher abundances of pteropods can easily be related to preservation since these aragonite producers dissolve at

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We can also note that the aragonitic pteropod abundance index as calculated by Lin in core PLO7-39PC shows the same trends as our rain ratio and GEX (Fig. 8). These higher abundances of pteropods can easily be related to preservation since these aragonite producers dissolve at...
Figure 7 Palaeoecological indicators for core 1002C. GEX and CEX are represented as 1-GEX for better comparison to the other proxies. Also shown are coccolith accumulation rates with 1-GEX overlaid, showing high dissolution concurrent with low accumulation. The alkenone record is from Herbert and Schuffert (2000) and the Mo/Al record is from Lyons et al. (2003).
Figure 8  Palaeoecological indicators for core PL07-39PC. Rain ratio, 1-GEX, 1-CEX, Fe/Ca and Mo/Al (Piper and Dean, 2002), Mg/Ca (Lea et al., 2003) and pteropod ratio (presented in reverse to facilitate comparison). The dark line highlights the lag in the terrigenous record.
shallower water depths than calcite due to the higher solubility in sea water (Morse and Arvidson, 2002). The near-absence of pteropods during the BA and Preboreal suggests that relatively intense dissolution during these intervals in the Cariaco basin would be difficult to relate to productivity.

A palynological analysis yielded records of dinoflagellate cysts per gram and pollen and spores per gram (unpublished data), next to alkenone concentrations (Herbert and Schuffert, 2000) (Fig. 7). These are all resistant components, which show high concentrations during periods of dissolution. On the other hand, higher pollen and spore concentrations could be related to higher river input, and the higher dinoflagellate cyst abundances could be related to large shifts in the assemblage from a heterotrophic to an autotrophic assemblage, which can be related to changes in the upwelling system. Higher alkenone concentrations can also be related to higher productivity of coccolithophores during these intervals.

We can also note that the change to a *G. oceanica* dominated flora is synchronous to a relative abundance change to centric diatoms, mainly coastal *Cyclotella* spp., a coastal diatom indicative of low production in warm, stratified and nutrient-limited waters of the summer and early fall (Barron et al., 2005). On the other hand, these robust diatoms could also reflect a preservational effect.

Fluctuations of GEX are also synchronous to a Mg/Ca SST reconstruction by Lea et al. (2003) on core PL07-39PC (Fig. 8). From an ecological viewpoint, the warming during the BA and Preboreal fits well with the relative abundance of *G. oceanica* increasing during these warming events (see ‘Ecology as interpretation’, above). This proxy would be unaffected by dissolution since Mg/Ca ratios decrease with increasing dissolution, and thus Mg/Ca temperatures are lowered.

There is also a good relationship between GEX and the Mo/Al record from PL07-39PC of Piper and Dean (2002) and (1002C) of Lyons et al. (2003) (Figs. 7 and 8). Higher Mo/Al ratios can be related to elevated anoxic bottom-water conditions (Lyons et al., 2003), which can be related to lower upwelling rates according to our model (Fig. 9). This is harder to explain by variations in preservation.

**Conclusion**

The tentative scheme is summarised in Fig. 9. To what extent the fluctuations are caused by dissolution and/or ecology should be tackled in future research. However, there is no doubt that productivity and preservation are tightly linked. We assume then that differences in productivity between both locations could explain dissolution being greater in the PL07-39PC core. Either way, GEX is apparently well suited as an upwelling proxy.

**Changes in the lower photic zone flora (LPZ)**

*F. profunda, T. flabellata and H. perplexus* (LPZ) live in well-stratified, low-temperature (<10°C), nutrient-rich sub-thermocline waters (Okada, 1983). It is generally accepted that these species have an inverse relationship to both productivity and upwelling (Okada and Matsuoka, 1996). Conversely, the surface water can be enriched in nutrients as a result of increased terrigenous materials and shallowing of the thermocline based on changes of the N ratio (abundance of reticulofenestrids (*E. huxleyi* and *Gephyrocapsa* spp.) relative to the LPZ flora) (Flores et al., 2000).
The lower N ratio confirms a higher stratification in the Cariaco Basin during the BA and the Holocene, and a weakening of the stratification (higher N ratio) during the glacial period and YD, where the strong upwelling inhibits photic zone development (Fig. 7). These changes in stratification can also be related to the influx of nutrient-rich SUW during sea level rise. In the Caribbean, abundance of LPZ flora track the presence of the SUW (Kameo, 2002). The lower sea level during the LGM would have obstructed SUW influx into the basin (Haug et al., 1998) and would have given an additional feedback by delimiting deeper photic zone development. It is clear, however, that deeper photic zone development is not completely dependent of SUW influx since even during the LGM, when this influx would be non-existent, this deeper photic zone flora is still present (Fig. 3).

Link to migrations of the ITZ

As for an ecological interpretation of the GEX upwelling proxy, any explanation for changes in the upwelling regime on a longer timescale in the Cariaco Basin would call upon migrations of the ITZ. When the ITZ is at a more southerly position, the upwelling cycle will be dominant, and if the ITZ is at a more northerly position the river input would be higher. In an ideal model for ITZ migrations over the Cariaco Basin, we would expect to see increases in the upwelling record to go hand in hand with decreases in the terrigenous record and vice versa. As a proxy for terrigenous input we use Fe/Ca (and Ti/Ca, which shows similar fluctuations), calculated from data from Piper and Dean (2002), similar to Jennerjahn et al. (2004). This has the advantage that, compared to Ti%, as used by Haug et al. (2001), this corrects for high carbonate inputs, which can be related to marine productivity (carbonate and silicilastic debris make up major components in the sediment and are inversely related (Piper and Dean, 2002)). So, if we compare the marine upwelling record revealed by GEX (and rain ratio, Mg/Ca), with Fe/Ca (Fig. 8), trends are quite similar, except at 9 ka BP, where there seems to be a short lag in the terrigenous record, possibly because of hydrological changes (Jennerjahn et al., 2004), influence by lateral advection (Astor et al., 2003) or aeolian transport (Yarinick et al., 2000). Nevertheless, the records suggest synchronous changes in both terrigenous and marine record, linked to migrations of the ITZ, which enables us to use the GEX as a proxy to trace migrations of the ITZ.

Palaeoclimate reconstruction

During the LGM, the sea level in the Caribbean Sea dropped by about 121 m (Fairbanks, 1989), exposing the Tortuga Bank to the north and restricting influx into the Cariaco Basin to a narrow channel to the west of the bank. Because of the relative height of the sill, only oligotrophic waters could enter, since SUW influx was obstructed. Thus, despite an increase in trade wind intensity during the LGM and Heinrich event 1 (upwelling as shown by GEX), no excessive plankton blooms occurred, the bacterial demand for oxygen was reasonable, the bottom waters were oxic and the accumulating basin sediments were not varved (Peterson et al., 1991, 2000; Haug et al., 1998; Yarinick et al., 2000).

The interstadial BA would have been characterised by a northern shift of the ITZ, and thus higher precipitation and lower upwelling (GEX). Higher productivity caused by increased influx of SUW together with the high river input and less upwelling would cause stratification of the basin (N ratio), and the development of anoxic bottom-water conditions, causing carbonate dissolution (reduction in carbonate accumulation).

During the stadial YD, with its shutdown of NADW formation, a sudden shift of the ITZ to the south would have occurred, with high upwelling rates (Peterson et al., 1991; Werne et al., 2000). This is confirmed by a high N ratio and GEX. After the YD, a sudden northern shift would induce high river influx during the Preboreal period, which would have been followed by a gradual southern shift of the ITZ up to the Holocene thermal maximum. After the Holocene thermal maximum, from about 6600 a on, the climate would be getting wetter, reflecting a gradual northern shift.

Conclusions

Coccoliths are useful palaeoecological indicators for migrations of the ITZ in the Cariaco Basin, as demonstrated by the new GEX index. Both syndepositional dissolution and ecological considerations explain variations in this record. A northern shift of the ITZ during the BA and Preboreal would alternate southern shifts during the YD and the middle Holocene. There seems to be little discrepancy between the upwelling and terrigenous record.

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References


Appendix: alphabetic species list

Acanthoa maxima Heimdal, 1981
Acanthoa quattropotina Lohmann, 1903
Agirospaera robusta (Lohmann, 1902) Norris, 1984
Calciohippus rigidus Heimdal, in Heimdal and Gaarder, 1981
Calciscus leptoporus (Murray and Blackman, 1898) Loeblich and Tappan, 1978
Calcosolenia Gran, 1912
Ceratolithus cristatus Kaptmier, 1950
Coronasphaera mediterranea (Lohmann, 1902) Gaarder, in Gaarder and Heimdal, 1977
Discosphaera tubifera (Murray and Blackman, 1889) Ostenfeld, 1900
Emiliania huxleyi (Lohmann, 1902) Hay and Mohler, in Hay et al., 1967
Florisphaera profunda Okada and Honjo 1973
Gephyrocapsa caribbeanica Boudreux and Hay, in Hay et al., 1967

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COCCOLITH PALAEOECOLOGY IN THE CARIACO BASIN

Gephyrocapsa ericsonii McIntyre and Bé, 1967
Gephyrocapsa oceanica Kamptner, 1943
Gladiolithus flabellatus (Halldal and Markali 1955) Jordan and Chamberlain, 1993
Hayaster perplexus (Bramlette and Riedel, 1954) Bukry, 1973
Helicosphaera carteri (Wallich, 1877) Kamptner, 1954
Helicosphaera pavimentum Okada and McIntyre, 1977
Michaelsarsia adriaticus (Schiller, 1914) Manton et al., 1984
Michaelsarsia elegans Gran 1912, emend. Manton et al., 1984
Pontosphaera discopora Schiller, 1925
Pontosphaera japonica (Takayama, 1967) Nishida, 1971
Reticulofenestra parvula (Okada and McIntyre, 1977) Biekart, 1989
Reticulofenestra sessilis (Lohmann, 1912) Jordan and Young, 1990
Rhabdosphaera clavigera Murray and Blackman, 1898
Syracolithus dalmaticus (Kamptner, 1927) Loeblich Jr and Tappan, 1966
Syracosphaera pulchra Lohmann, 1902
Syracosphaera Lohmann, 1902
Umbellosphaera irregularis Paasche, in Markali and Paasche, 1955
Umbellosphaera tenuis (Kamptner, 1937) Paasche, in Markali and Paasche, 1955
Umbilicosphaera sibogae (Weber-Van Bosse, 1901) Gaarder, 1970