Deep-Sea Research I 56 (2009) 2249–2262

Contents lists available at ScienceDirect

Deep-Sea Research I

journal homepage: www.elsevier.com/locate/dsri

The importance of subsurface nepheloid layers in transport and delivery of sediments to the eastern Cariaco Basin, Venezuela

Laura Lorenzoni [a,*], Robert C Thunell [b], Claudia R. Benitez-Nelson [b,c], David Hollander [a], Nahysa Martinez [d], Eric Tappa [b], Ramón Varela [e], Yrene Astor [e], Frank E. Muller-Karger [a]

[a] University of South Florida, College of Marine Science, 140 7th Ave. S., St. Petersburg, FL 33701, USA
[b] University of South Carolina, Department of Geological Sciences, Columbia, SC 29208, USA
[c] University of South Carolina, Marine Science Program, Columbia, SC 29208, USA
[d] Department of Earth Sciences, Boston University, Boston, MA 02215, USA
[e] Fundación La Salle de Ciencias Naturales, EDIMAR, Apdo. 144, Porlamar, Edo Nueva Esparta, Venezuela, USA

ARTICLE INFO

Article history:
Received 8 August 2008
Received in revised form
31 July 2009
Accepted 3 August 2009
Available online 13 August 2009

Keywords:
Nepheloid layers
Cariaco Basin
Particulate organic matter
Sediment transport

ABSTRACT

Optical transmissometer measurements were coupled with particulate organic matter (POM) observations to understand suspended sediment composition and distribution in the eastern Cariaco Basin during the rainy seasons of September 2003 and 2006. Our results suggest that nepheloid layers originating at the mouth of small mountainous rivers discharging into the eastern Basin are a major delivery mechanism of terrigenous sediments to the Basin interior. Intermediate nepheloid layers (INL) were observed near the shelf break (~100 m) and appear to effectively transport terrigenous material laterally from the shelf to deep waters, thereby providing a plausible supply mechanism of the terrestrial material observed in sediment traps. These findings highlight the importance of small, local rivers in the Cariaco Basin as sources of terrestrial material. In contrast, these nepheloid layers contained only limited POM. When this information is combined with published sediment trap POM data, it suggests that nepheloid layers may not be a primary mechanism for delivering terrigenous POM to the deeper waters of the basin during the rainy season. Rather, BNL may redistribute marine-derived POM from shallow waters to the Basin's interior by providing ballast materials, particularly during episodic events driven by wind and precipitation. Though we have determined that nepheloid layers play an important role in the seaward transport of particulate material in the Cariaco Basin, their composition and temporal variability have not been fully characterized. This is critical to understand lateral particle transport, since nepheloid layers constitute a significant source of sediment to the deep Cariaco Basin.

Published by Elsevier Ltd.

1. Introduction

Understanding the transport of lithogenic material from land to sea is critical for understanding sedimentary sinks of a wide range of particle active elements, including carbon, nutrients and trace elements (Brunskill, 2009). For example, it has been hypothesized that more than 80% of particulate organic carbon is buried on continental margins (e.g. Hedges and Keil, 1995) and recent evidence suggests that a significant portion of this organic carbon is continentally derived (Goñi et al., 2008). Rivers are the main conduit of sediment to the coastal ocean. Their sediment load is a function of basin geology, drainage area, discharge rate and human activity (Milliman and Syvistski, 1992). As sediment yield increases with increasing drainage basin and decreasing basin size, small rivers

---

* Corresponding author: Tel.: +1 727 553 1186; fax: +1 727 553 1103.
E-mail address: laural@marine.usf.edu (L. Lorenzoni).

0967-0637/$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.dsr.2009.08.001

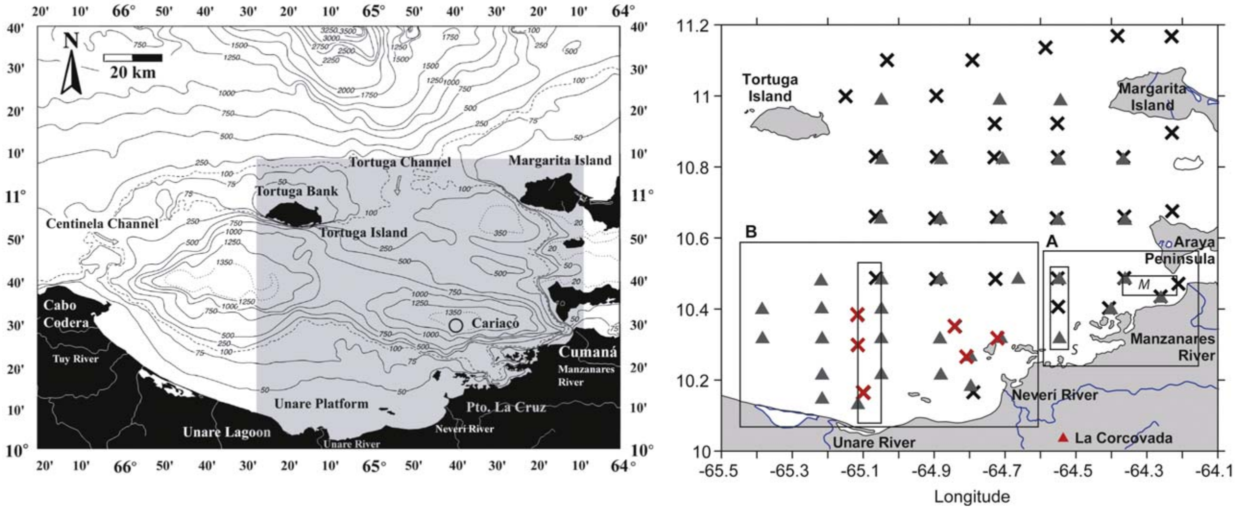

Fig. 1. (Left) Bathymetric map of the Cariaco Basin. Circle indicates location of CARIACO Time Series sediment trap array. Shadowed rectangle indicates area of study. (Right) Area of study. Sampling locations for September 2003 (diamonds) and 2006 (crosses). Red crosses indicate sample location for suspended particulate matter in 2006. Red triangle indicates location of the Corcovada meteorological station. The coastal area is divided into regions A and B. Rectangles M and S within Region A indicate location of transects in Fig. 5. Rectangle within Region B indicates location of transect in Fig. 6.

draining steep coastal watersheds have the potential to transport large amounts of suspended sediments to the coastal ocean (Inman and Jenkins, 1999; Hicks et al., 2004). Smaller watersheds are also susceptible to episodic flooding due to high precipitation events, during which large quantities of sediments can be delivered to the coastal ocean (Milliman and Syvistski, 1992; Walsh and Nittrouer, 1999; Hill et al., 2000; Wheatcroft, 2000; Kao et al., 2006; Goldsmith et al., 2008).

Once the sediment is discharged onto the shelf, a variety of processes affect its distribution (Sahl et al., 1987; Trowbridge et al., 1994). In river-dominated continental margins, sediment distribution is controlled to a large degree by lateral dispersal and deposition, rather than direct vertical settling. Subsurface nepheloid layers are of particular interest as they may transport significant quantities of sediment over long distances, from the coastal environment to the deep sea (McCave et al., 2001; Pak et al., 1980; McPhee-Shaw et al., 2004; Inthorn et al., 2006). Bottom nepheloid layers (BNL) are found in the lower water column and are characterized by increased particle concentrations relative to surrounding waters. Intermediate nepheloid layers (INL) are similar, but occur at intermediate water depths; they are usually found near continental shelves and slopes and are associated with strong density gradients (McPhee-Shaw et al., 2004; Inthorn et al., 2006). Nepheloid layers vary spatially and temporally (they can be permanent or transitory) and their intensity and thickness depend on local conditions (McPhee-Shaw et al., 2004; Inthorn et al., 2006). Optical techniques have proven to be one of the most effective ways to rapidly observe nepheloid layer characteristics and distributions (Dickson and McCave, 1986; Gardner, 1989).

Here, we examine both suspended and sinking particles collected over the southern margin of the eastern Cariaco Basin (Venezuela) as part of the CARIACO Time Series program. The goal of this study is to better understand the influence of local rivers on the supply of terrestrial material to the Basin and to assess the role of bottom nepheloid layers (BNL) and intermediate nepheloid layers (INL) as mechanisms in the lateral transport and delivery of terrigenous sediment (and terrestrially derived organic matter) from the coast to the deep waters of the Basin's interior.

2. Methods

2.1. Study area

The Cariaco Basin (Fig. 1) is an east–west trending pull-apart basin (Schubert, 1982) located on the continental shelf off eastern Venezuela. This deep depression is composed of two sub-basins, eastern and western, each ~1400 m deep and separated by a saddle of ~900 m. To the south, the basin confines the wide (~50 km), gently sloping, shallow (100 m depth) Unare Platform. It is connected to the Caribbean Sea through two shallow (~140 m) channels to the north (Tortuga Channel) and to the west (Centinela Channel). Water circulation within the basin is restricted, which, combined with the high annual primary productivity of the region (~500 $g\,cm^{-2}\,yr^{-1}$), causes the basin to be permanently anoxic below ~250 m (Muller-Karger et al., 2001, 2004). Its unique geography and laminated sediments provides an excellent record of tropical climate change that is particularly sensitive to shifts in the Intertropical Convergence Zone (ITCZ) (Hughen et al., 1996; Peterson et al., 2000; Peterson and Haug, 2006, Black et al., 2007).

Several small rivers drain into the Cariaco Basin, including the Tuy, Unare, Manzanares and Neverí (Table 1, Fig. 1). The Unare, Manzanares and Neverí, located towards the east, contribute an estimated

1.16×10^6 tons of sediment per year (Milliman and Syvistski, 1992; INIA-MARN, 2003). The Manzanares and Neverí cross the Serranía del Interior formation, which is part of the Cordillera de la Costa mountain range and is composed of Mesozoic metamorphic and igneous rocks. The Unare River has one of the most extensive drainage basins in northern Venezuela. It runs through the Unare Depression and drains sedimentary rocks of Cretaceous and Tertiary age (Morelock et al., 1972; PDVSA, 1992; Martinez et al., 2007). The Tuy River discharges directly into the western Cariaco Basin. It has the highest mean annual load of the four rivers described here (12×10^6 tons of sediment per year; Table 1, Milliman and Syvistski, 1992).

2.2. *Data collection*

Two oceanographic research cruises, COHRO 1 and CASEP 2, were conducted in September 2003 and 2006, respectively, aboard the *R/V Hermano Ginés* of the Fundación la Salle de Ciencias Naturales de Venezuela. Station locations were similar for both cruises (Fig. 1). This is the rainy season in the southern Caribbean Sea; sampling during the month of September, well into the rainy season, assured us we would be able to observe the influence of the rivers in full (Astor et al., 1998). Salinity and temperature profiles were collected at each site with a Seabird SBE25 CTD mounted on a rosette with 128-l Niskin-like bottles. Chlorophyll fluorescence and beam attenuation at 660 nm ($c_p(660)$, m^{-1}) profiles were obtained with an $\text{AQUA}^{\text{traka}}$ fluorometer (Chelsea, Inc.) and a C-Star (WetLabs) 25 cm pathlength transmissometer attached to the CTD. The mixed layer depth (MLD) was estimated as the depth at which the potential density change was greater than 0.01 $\mathrm{kg\,m^{-3}}$ (Thompson and Fine, 2003). Sigma–theta (σ; $\mathrm{kg\,m^{-3}}$) was derived from the CTD temperature and salinity using the same Seabird software used to process the rest of the parameters (Seasave Win32 V 5.35a). During 2006, water samples for suspended sediment analyses were collected from multiple depths in the water column at six stations (marked in red in Fig. 1, Table 2). Water was drained into acid-cleaned tubs, and filtered through a precombusted (450 °C for 5 h) GF/F filters (0.7 μm pore size) using an in-line polycarbonate filter holder and a submersible pump. Samples were gently stirred during filtration to avoid accumulation of the suspended matter on the bottom of the tub. Filters were refrigerated until arrival on shore. The filters were then dried for several hours at 60 °C and geochemical analyses performed (see below). Samples for dissolved organic carbon (DOC) were collected at the surface using precombusted (450 °C for 5 h) GF/F filters (0.7 μm pore size) and polycarbonate in-line filter holders. Samples for total organic carbon (TOC) were also collected by storing

Table 1
Characteristics of main rivers feeding the Cariaco Basin.

River	Drainage area ($10^3\,\mathrm{km}^2$)	Flow rate ($\mathrm{m^3\,yr^{-1}}$)	Load ($\times10^6\,\mathrm{t\,yr^{-1}}$)
Tuy	6.6[a]	2.59[a]	12[c]
Unare	22.5[b]	1.98[b]	1.12[b]
Neverí	3.9[a]	1.10[a]	0.29[c]
Manzanares	1.0[a]	0.69[a]	0.2[c]

[a] Zink (1977).
[b] INIA-MARN (2003).
[c] Milliman and Syvistski (1992).

Table 2
Geochemical results for selected sampled stations.

Station no.	Lat/lon	Station bottom depth (m)	Depth sampled (m)	Volume filtered (L)	Particle conc. ($\mathrm{mg\,L^{-1}}$)	POC ($\mathrm{\mu g\,L^{-1}}$)	PN ($\mathrm{\mu g\,L^{-1}}$)	POP ($\mathrm{\mu g\,L^{-1}}$)	PIP ($\mathrm{\mu g\,L^{-1}}$)	δ^{13}C (‰)	C/N (molar ratio)	C/TPP (molar ratio)	C/PIP (molar ratio)	C/POP (molar ratio)	%PIP
60	10.18°N/ −65.08°W	27	1	3.58	1.72	111.37	10.2	1.23	0.3	−24.04	12.7	188	959	234	0.196
			26	**2.27**	**2.74**	**128.48**	**13.55**	**1.4**	**1.05**	**−24.47**	**11.1**	**135**	**316**	**237**	**0.429**
37	10.31°N/ −65.10°W	65	13	4.17	1.24	96.67	10.53	1.16	0.3	−23.84	10.7	171	832	215	0.205
			55	**4.8**	**1.74**	**82.42**	**9.6**	**0.69**	**0.37**	**−23.1**	**10.0**	**201**	**575**	**309**	**0.349**
39	10.36°N/ −64.83°W	75	13	4.33	1.46	94.57	9.98	0.96	0.45	−23.89	11.1	173	543	254	0.319
			66	**4.43**	**1.84**	**94.89**	**9.81**	**0.55**	**0.7**	**−23.14**	**11.3**	**196**	**350**	**446**	**0.560**
27	10.33°N/ −64.71°W	54	10	4.16	1.73	138.49	16.49	0.69	0.45	−23.36	9.8	314	795	519	0.395
			48	**4.63**	**1.76**	**93**	**9.61**	**0.73**	**0.29**	**−23.39**	**11.3**	**236**	**828**	**329**	**0.284**
35	10.28°N/ −64.80°W	55	12	4.39	1.44	77.56	8.48	0.35	0.54	−23.85	10.7	225	371	572	0.607
			50	**4.43**	**1.47**	**83.39**	**8.25**	**0.82**	**0.77**	**−23.34**	**11.8**	**135**	**280**	**263**	**0.484**
38	10.39°N/ −65.10°W	71	11	4.04	1.53	95.54	10.26	1.11	0.45	−22.12	10.9	158	548	222	0.288
			66	**4.35**	**1.47**	**79.63**	**7.76**	**0.51**	**0.26**	**−20.60**	**12.0**	**267**	**791**	**403**	**0.338**

Bold numbers indicate bottom nepheloid layer location.

unfiltered water samples taken directly from the Niskin bottle into HDPE bottles. Both DOC and TOC samples were kept frozen at −20 °C until analyzed (Dickson et al., 2007).

2.3. Geochemical analyses

Particulate organic carbon (POC) and nitrogen (PN) were measured simultaneously with δ^{13}C and δ^{15}N using a Fison NA 1500 Elemental Analyzer (Werne and Hollander, 2004; Thunell et al., 2007). The standard used was Spinach Leaves (NIST 1570a). The operational precision for the isotopic compositions were ±0.32‰ for δ^{15}N and ±0.24‰ for δ^{13}C. For POC and PN, the operational precision was ±0.02 mg C and ±0.14 mg N. Filters were tested for carbonate concentrations by comparing acidified and not acidified duplicate suspended particle filters. The results showed that filters agreed to within 85%, with no statistical difference in POC concentration ($p > 0.05$). Given the low carbonate concentrations observed, suspended particle filters were not acidified prior to combustion. Thus, suspended filter POC concentrations may be slightly overestimated. Total particulate P (TPP) and particulate inorganic P (PIP) were measured following the methods described by Benitez-Nelson et al. (2007). Particulate organic phosphate (POP) was estimated by difference from TPP and PIP. TPP and PIP measurements have a standard error of 6%, while POP has a standard error of 8.5%. DOC and TOC were analyzed by the Organic Biogeochemistry Lab at the University of Miami (RSMAS) using high temperature catalytic oxidation (HTCO). Their accuracy is ±1.0 μM C.

2.4. Meteorological data

Wind and precipitation were measured at Punta de Piedras (Margarita Island) and Corcovada (mainland Venezuela), respectively (Fig. 1). The station at Punta de Piedras is maintained by the Fundación La Salle de Ciencias Naturales, while the station at Corcovada is maintained by the Venezuelan Department of the Environment (Ministerio del Poder Popular para el Ambiente/MINAMB). The Punta de Piedras station has recorded winds since 1975. Corcovada station only has records of precipitation from 1995 to 2000 (MINAMB). River discharge responds to precipitation in the river basin. Thus, the Corcovada station was used to examine patterns

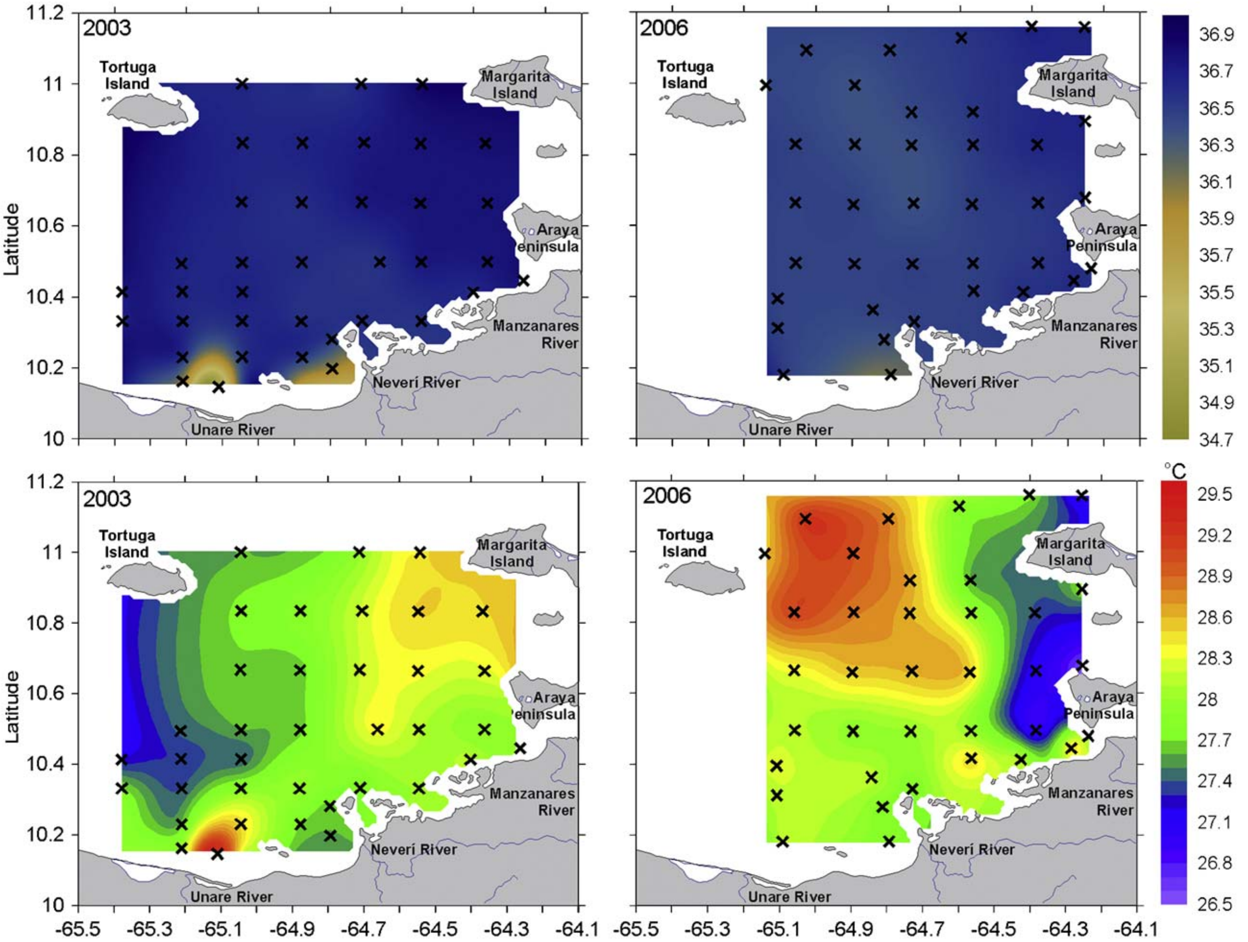

Fig. 2. Distribution of salinity (top) and temperature (bottom) during September 2003 and 2006. Main rivers are shown (blue lines; For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.). X indicates station location.

related to precipitation because it best captures precipitation over the Unare, Neverí and Manzanares watersheds. Additional meteorological data are limited in this region.

2.5. Visualization of the data

Surfer (Golden Software, Inc.), V.8.04, was used to generate the spatial distribution maps. Minimum Curvature was chosen as the gridding method to produce the interpolated surfaces. Sigmaplot V.10.0 (Systat Software, Inc.) was used to generate Fig. 7.

3. Results

Fig. 2 shows sea surface (1 m) salinity and temperature in the eastern Cariaco Basin for September 2003 and 2006. In September 2003, the Unare River plume had lower salinity (35.38) and warmer (28.97 °C) temperature than surrounding waters ($\sim$27.7 °C). The Neverí and Manzanares river plumes were slightly cooler (27.57 and 28.03 °C, respectively), and average salinities near the mouths of these rivers were 36.01 and 36.75, respectively. During September 2006, salinities (and temperatures) recorded near the mouths of the Unare, Neverí and Manzanares rivers were 36.46 (28.20 °C), 36.23 (27.87 °C) and 36.53 (28.05 °C), respectively.

The sea surface temperature distribution around the Cariaco Basin during the rainy season depends largely on basin stratification (Astor et al., 1998). During September 2006, average MLD near the coast was $\sim$4 m, increasing to $\sim$16 m in areas $>$100 m. South of Margarita Island, between Margarita and the western tip of the Araya Peninsula, the MLD averaged 14 m. This, coupled with strong surface ($\sim$0–10 m) ocean currents observed in this area ($>$30 cm s^{-1}) suggest that weak upwelling was responsible for the cold waters (26.78 °C) measured at the surface (compared to the average sea surface temperature of 28.24 °C measured in the rest of the Cariaco Basin; Fig. 2).

Fig. 3 illustrates the surface (1 m) distribution of TOC and DOC during September 2006. The DOC and TOC around the basin, and especially near the coast, provided information on the portion of particulate and dissolved organic carbon the rivers were contributing, as well as the extent and distribution of this material offshore. Higher TOC was observed near the Unare River (average of 85.4 μM) and between Margarita Island and the Araya Peninsula (average of 79.1 μM), relative to the rest of the basin (average of 71.5 μM). Higher DOC was also observed to the southeast of the Basin, but not over the Unare Platform. Since there are no large rivers draining Margarita Island, the cause of the high DOC and TOC observed between Margarita and the Araya Peninsula was likely the result of local upwelling. The elevated organic carbon to the south of Cumaná was more likely the product of local river discharge from the Manzanares River, which supplies the basin with high concentrations of both particulate and dissolved carbon (Rasse and Lorenzoni, unpublished data). There was relatively little DOC transported into the basin by the southern rivers (Unare and Neverí), with most of the particulate carbon settling close to the coast ($<$15 km from the mouths of the rivers) as suggested by the TOC data.

The beam attenuation ($c_p(660)$) measured during September 2003 and 2006 are shown in Fig. 4. The particulate beam attenuation at 660 nm describes the loss of light due to the presence of particles, since attenuation due to dissolved materials is negligible in this part of the spectrum. Hence, c_p can be used as a relative measurement of particle concentration in the water (Boss et al., 2001; Behrenfeld and Boss, 2003). High beam attenuation ($\sim$1 m^{-1}) was observed at the surface (1–2 m) near the mouths of the three rivers (Fig. 4, top panels), corresponding to particulate material being discharged into the basin by rivers. Surface TOC and surface $c_p(660)$ showed a positive correlation near the coast ($R^2 = 0.64$, $N = 14$; $\alpha < 0.01$) indicating a high concentration of organic matter in the upper waters. Both TOC and surface $c_p(660)$ decreased within a short distance from the river mouths,

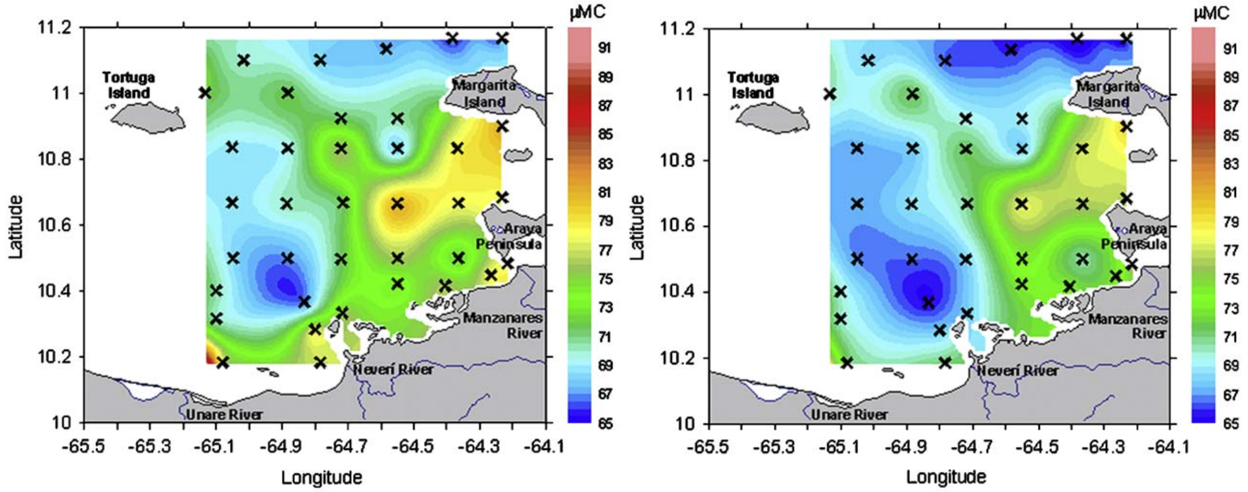

Fig. 3. surface distribution of TOC (left) and DOC (right) in the eastern Cariaco Basin during September 2006. X indicates station location.

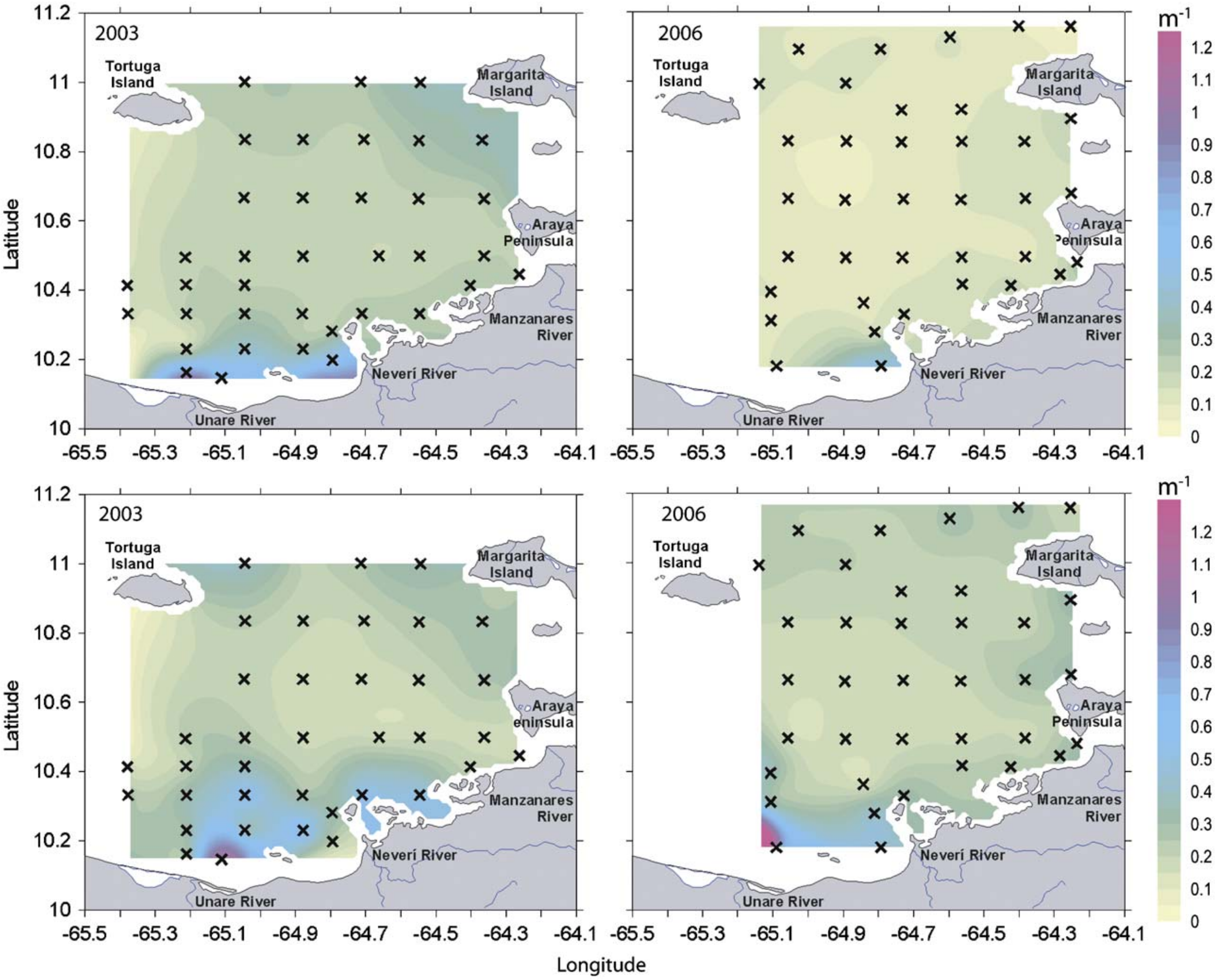

Fig. 4. Distribution of surface (SNL; top) and bottom (BNL; bottom) nepheloid layers, measured as beam attenuation ($c_p(660)$, m^{-1}) during September 2003 and 2006. X indicates station location. Contours are set to $0.05\,m^{-1}$ increments.

suggesting that most riverine particles settle from surface waters rapidly. High attenuation was also observed between 3 and 20 m above bottom (m.a.b.) throughout the entire coastal area, with highest values ($\sim$0.6–1 m^{-1}) near the mouths of the rivers (Fig. 4, bottom panels). The high beam attenuation observed near the seafloor was due to suspended sediment forming BNLs. The thickness and location of the BNL were similar during both 2003 and 2006.

The area of study was divided into two regions near the coast: A and B (Fig. 1). These regions constitute two areas of the eastern Cariaco Basin that have different bathymetry and thus, dissimilar sediment distribution patterns. Region A constitutes the Manzanares Submarine Canyon and the area southwest of the city of Cumaná. It has a steep topography and a narrow shelf (on the order of 10 km or less). Region B has the gently sloping and wide ($\sim$50 km) continental shelf characteristic of the Unare platform.

The BNL in Region A (average $c_p(660)$ of 0.3–0.4 m^{-1}) were not well developed and were mostly detached from the bottom ($\sim$10 m.a.b). Representative beam attenuation and density distribution for two locations in this region are shown in Fig. 5. A surface nepheloid layer (SNL) was measured near the mouth of the Manzanares River. Distinct intermediate nepheloid layers (INLs) were observed as a small increase in beam attenuation and were associated with isopycnals, moving roughly over the same density surface ($\sigma = 25.37$–$25.43\,kg\,m^{-3}$ over the Manzanares Canyon; Fig. 5 top. $\sigma = 26.1\,kg\,m^{-3}$ southwest of Cumaná; Fig. 5 bottom). The INLs measured around Region A varied in thickness (between 14 and 6 m), decreasing in thickness with increasing distance from the coast.

A schematic representation of the nepheloid layer distribution across a transect over Region B is shown in Fig. 6. The BNLs (average $c_p(660)$ of 0.5–0.6 m^{-1}) were well developed and extended northeastward along the Unare Platform. They varied in thickness, from about 5 m thick near the Unare River to 6–15 m thick near the Neverí River. Surface nepheloid layers (SNLs) were measured near the mouth of both rivers. The BNLs extended out to the 100 m isobath, increasing in thickness (up to three-fold) towards the shelf break. Off the Unare Platform and over the deep Cariaco Basin, slightly increased $c_p(660)$ values

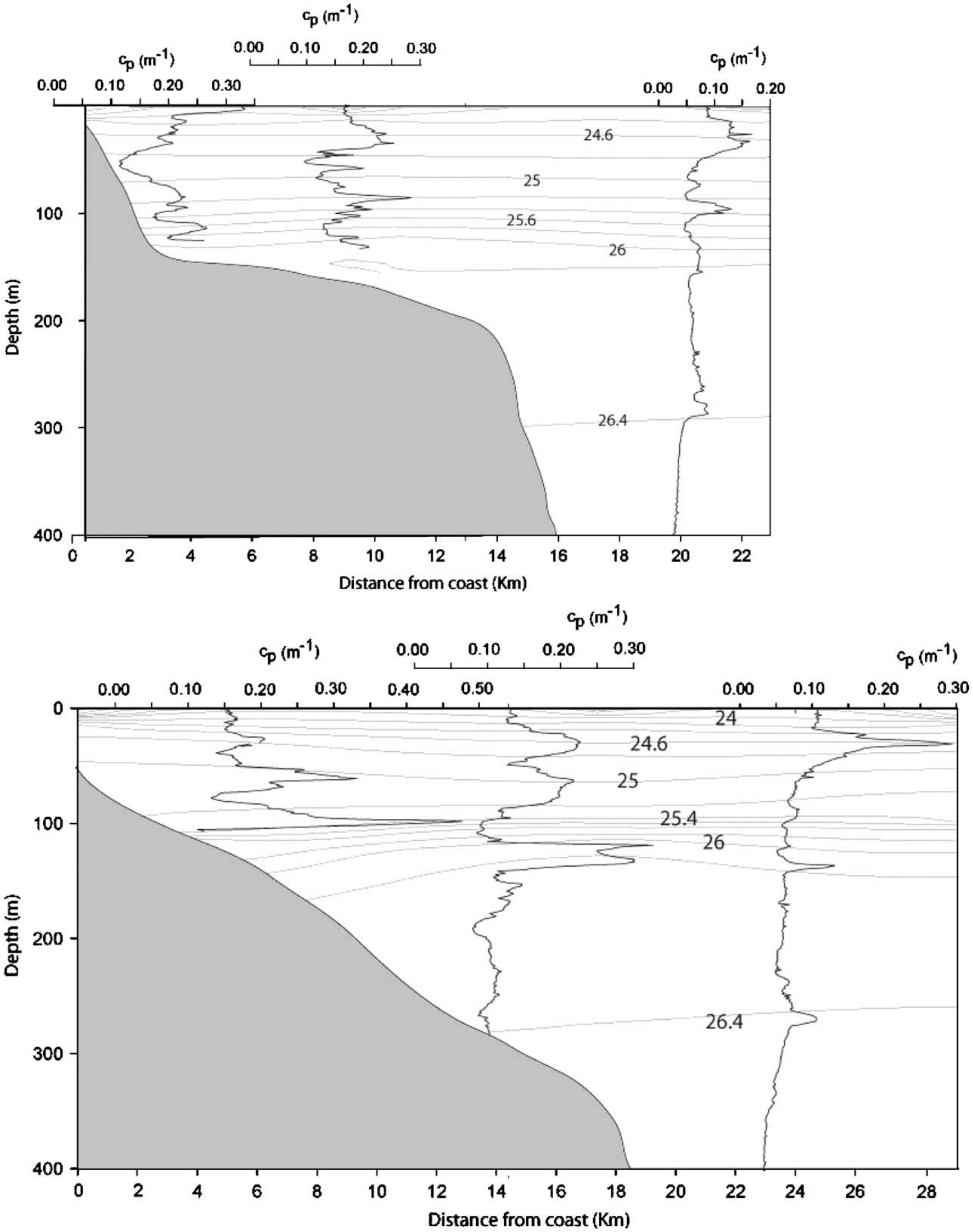

Fig. 5. Distribution of beam attenuation (c_p (m^{-1})) and major isopycnals (kg m^{-3}) for selected locations over Region A (refer to Fig. 1 for location). Region M (top) is located near the Manzanares Submarine Canyon. Region S (bottom) is located over the shelf.

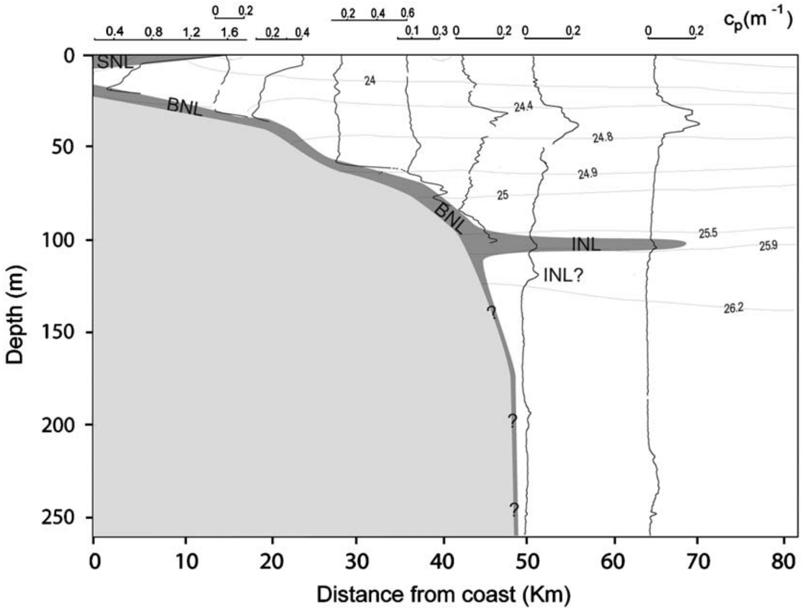

Fig. 6. Schematic distribution of nepheloid layers across the Unare Platform (Region B, refer to Fig. 1 for location) based on beam attenuation data (black lines). SNL indicates surface nepheloid layer; BNL and INL denote bottom and intermediate nepheloid layers, respectively. Major isopycnals (kg m^{-3}) are also shown. Note that for better visualization of INL's, scales of offshore profiles have been resized.

indicated the presence of INLs. These INLs were closely associated with the pycnocline and were observed over 60 km from the coast, with an average thickness of ~10 m.

Particulate organic matter analyses conducted within the BNL showed concentrations that were similar to those observed in the overlying water column. There was also no apparent correlation between BNL beam attenuation intensity and organic matter content, as observed in other regions (Karp-Boss et al., 2004), suggesting that the bulk of the attenuation was due to inorganic particles (Table 2). This was confirmed to some extent by the PIP data, which was more than a factor of two higher within the nepheloid layers of the shallowest station. Interestingly, the C/POP ratios showed a general increase in the offshore direction, especially in the nepheloid layers. This suggests a preferential removal of POP as the BNLs move offshore. In contrast, the C/PIP ratios were quite low, and continued to be low further offshore, suggesting retention of PIP. The δ^{13}C (−23‰ to −24‰), C/N ratios and PIP signals within the BNL suggest a mixed terrigenous-marine source for the POM and inorganic nutrients, with the signal becoming less terrestrial (more marine) with increasing distance from the coast. We hypothesize that this is due to the addition by marine-derived organic matter and the settling of terrestrially derived organic and inorganic materials with increasing distance offshore.

4. Discussion

4.1. Importance and distribution of subsurface nepheloid layers

Small rivers can have high sediment loads (Milliman et al., 1999), especially during episodic events such as floods and landslides. One such example was the catastrophically high precipitation that affected the Venezuelan coast during November and December 1999. The mixture of "Nortes" (Lyon, 2003) and La Niña conditions in the Equatorial Pacific created the conditions that supported sustained, torrential rains along Cordillera de la Costa. The effects were most pronounced in the central part of Venezuela, where mudfloods and landslides claimed over 15,000 lives and over US$1.8 billion in damage (Andressen and Pulwarty, 2001). In the central Cariaco Basin, at the location of the CARIACO Time Series site, the delivery of terrigenous material increased six-fold during the 1999 flood, from an average of 10.45 g m^{-2} month^{-1} measured during the November months to 69.34 g m^{-2} month^{-1} for that particular event (http://www.imars.marine.usf.edu/CAR/). Results from this study suggest that such large amounts of sediments were transported to the CARIACO site by subsurface nepheloid layers. Subsurface nepheloid layers constitute a major cross-shelf transport mechanism of particles from the coast to the deep Cariaco Basin. Evidence for BNL and INL as particle transport mechanisms has been documented elsewhere, including in the East Indies (Milliman et al., 1999; Kineke et al., 2000), the Benguela upwelling system (Inthorn et al., 2006), off England (Dickson and McCave, 1986), the East China Sea (Hung et al., 2007), the Mediterranean and Iberian shelf (Puig and Palanques, 1998; Oliveira et al., 2002), the Baltic Sea (Yurkovskis, 2005), and the western coast of the United States (Pak et al., 1980; Curran et al., 2002; Puig et al., 2003; McPhee-Shaw et al., 2004).

4.2. Nepheloid layer composition

During the study period (rainy season), the depleted carbon isotopic signature suggests that particles in the

BNL were initially continentally derived. This is confirmed by a number of other indirect studies. For example, Martinez et al. (2007) observed increases in the elemental ratios (Ti/Al, Fe/Al) of the sediment traps in the Cariaco Basin during the rainy season, suggesting a shift towards more lithogenic material. This is consistent with the 50% increase in PIP observed during this period as well (Benitez-Nelson et al., 2007). Elmore et al. (2009), studying the clay mineralogy of sediment samples collected in the basin, also concluded that high precipitation yielded more riverine-derived sediment in the nearshore, with the Unare River being the main source of clay-sized lithogenic particles.

The dynamics of the organic matter associated with nepheloid layers as it moves into deep water is less clear. Nepheloid layer POM concentrations were similar to or lower than that of the overlying water column and the isotopic ratios moved from a terrestrial to marine signature with increasing distance from the coast. This suggests that local rivers supply only limited amounts of terrestrially derived POC, PN and POP to the coastal environment and their distribution is restricted to the coastal area; particles settled out of the water column soon after entering the ocean (Table 2). Similar observations have been reported in the northwest Mediterranean (Puig and Palanques, 1998) and the East China Sea (Hung et al., 2007). This supports the findings of Goñi et al. (1997), Thunell et al. (2000) and Woodworth et al. (2004), who reported no significant contribution of terrestrial organic carbon in the CARIACO sediment traps.

4.3. Physical dynamics of nepheloid layers

The transport of the material from the nearshore to deep waters may be related to the physical dynamics that affect the residence times of particles within the nepheloid layers. In the Cariaco Basin, we found that the distribution of the nepheloid layers depended both on the hydrodynamics of the area, as well as the morphology. Region A is characterized by rapid changes in bathymetry and stronger currents (Alvera-Azcárate et al., 2008). In this region detached BNLs dominated the narrow shelf; the sharp topography, combined with higher energy circulation, appears to inhibit full BNL formation. The INLs measured offshore were related to the advection of the detached BNLs and spread along constant density surfaces away from the coast. INLs develop most commonly over continental slopes and are associated with isopycnals and internal tides, usually moving along-isopycnals after detaching from the shelf break (Pak et al., 1980; Azetsu-Scott et al., 1995; Oliveira et al., 2002; McPhee-Shaw et al., 2004; McPhee-Shaw, 2006). They are also found in and around submarine canyons. Based on our limited sampling, INLs in this area seemed to dissipate within 30 km from their site of origin. Their dispersal could potentially be controlled by local currents, which advect the INL eastward (Alvera-Azcárate et al., 2008), and/or by particle settling. INLs inside the Manzanares submarine Canyon were observed both in 2003 and 2006, potentially transporting horizontally advected shelf material (both resuspended and fresh) rapidly to depth. Hickey et al. (1986) determined that the dominant mode of sediment transport down Quinault Canyon (Washington coast) was by the episodic formation at intermediate depths of turbidity layers. Puig et al. (2003) also observed a persistent particle layer that contributed to off-shelf sediment transport in Eel Canyon (northern California). Puig and Palanques (1998) suggested that in continental margin canyons, such as the Foix Canyon (northwest Mediterranean Sea), sediment transport is dominated by INL detachments and internal waves. Near the Sepik River (Papua New Guinnea) down-canyon transport has also been observed, which disperses the sediment to more distal regions than would be possible by a simple surface plume (Kineke et al., 2000). Similarly, the Manzanares submarine canyon appears to directly funnel sediment discharged by the Manzanares River to the deep basin, particularly during episodic storms or geologic events (Lorenzoni et al., submitted).

In Region B, the wide Unare Platform allows for BNL to become well-developed, similar to what happens along the Texas shelf (Sahl et al., 1987). The BNL we measured in this area displayed a decrease in particle concentration and increase in thickness with increasing distance from the river mouths. Similar observations were made on the Barcelona continental margin off Spain (Puig and Palanques, 1998) and in the Celtic Sea (McCave et al., 2001). Two processes appear to maintain the nepheloid layers we observed in Region B: local river input and high energy coastal processes. The maximum concentration of particles recorded near the river mouths (2.74 mg L^{-1}, Table 2) suggests a lithogenic contribution by the rivers. With increasing distance from the coast, resuspension due to bottom currents, tides and near-inertial waves, probably play an important role in the maintenance of the BNL. McCave et al. (2001) observed an increase in BNL thickness with depth over the Goban Spur area, consistent with increased current velocities. Lentz and Trowbridge (1991) also found bottom mixed layer heights to be dependent on current velocity and direction, increasing with increasing currents. As the BNL reach the edge of the Unare Platform, they are subject to increase in current velocities. The Basin has a strong eastward subsurface current centered around 120 m, which on occasion reverses direction (Virmani and Weisberg, 2009). It is believed to be part of a basin-wide gyre (Alvera-Azcárate et al., 2008). During September 2006, strong eastward currents (>10 cm s^{-1}) were recorded at the edge of the Unare Platform, which suggests a two-fold velocity increase from the coast to the platform edge. The particulate matter transported horizontally through BNL give rise to INLs. Once the BNLs reach the edge of the Unare Platform they become suspended and extend toward the interior of the Cariaco Basin, generating a ‘shelf-break INL’ (Puig and Palanques, 1998). This type of INL has frequently been observed in other shelf-break areas and can be either permanent or transitory, depending on the dynamics of the shelf (Azetsu-Scott et al., 1995; McPhee-Shaw et al., 2004; Inthorn et al., 2006; McCave and Hall, 2002; Oliveira et al., 2002; Chronis et al., 2000). In the Cariaco Basin, these detached nepheloid layers were observed in both 2003 and 2006, suggesting they are a permanent feature during the rainy season. INLs in Region B were observed in association with the pycnocline, moving along this density surface and reaching over 60 km from their origin. This is almost twice as far as those INLs measured in Region A. The difference in the offshore extent of these INLs between the two regions may be related to the circulation and currents around the basin, as well as the association of the INLs of Region B with the pycnocline. The particularly strong density gradient that comprises the pycnocline likely acts as a region of particle accumulation that retains small particles as they are advected from the shelf via BNLs and allows for further transport over longer distances. This highlights the importance of INLs as significant mechanisms for lateral transport of particulate matter from the shelf into the deep basin. Deep INL (> 150 m) were also observed in certain locations of the deep basin (Figs. 5 and 6). Although there is no current explanation for their formation, they may be derived from intermittent erosion processes of the continental slope or resuspension by internal waves (Dickson and McCave, 1986; Oliveira et al., 2002; McPhee-Shaw et al., 2004).

4.4. Temporal variation and fate of horizontally transported particles

In order to assess temporal variations in particle transport and to understand the ultimate fate of particles originating on the continental shelf, we examined sediment

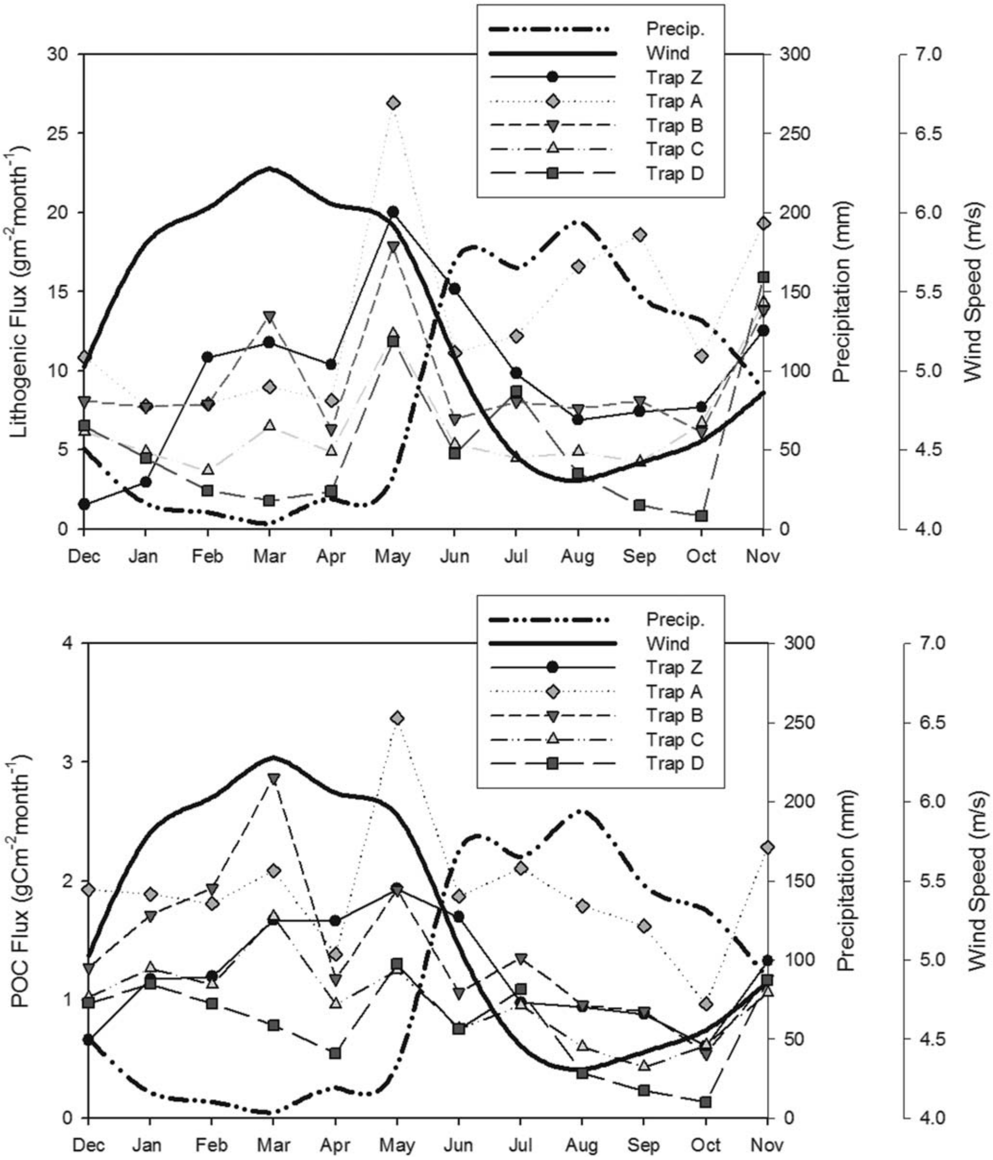

Fig. 7. Monthly average of lithogenic and POC fluxes between 1995 and 2006. Mean wind speeds and average precipitation are also shown.

trap particle flux data collected from the CARIACO Time Series program (Thunell et al., 2000, 2007, http://www.imars.marine.usf.edu/CAR/). The material captured by the sediment traps positioned at different depths in the center of the eastern Cariaco Basin provides a time-series of lateral transport of sediments off the shelf (atmospheric sources of this material are negligible; Martinez et al., 2007). The mooring is equipped with five sediment traps (Z, A–D). Traps A–D have been operational since November 1995 and are located at depths of 225, 410, 810 and 1200 m, respectively (Thunell et al., 2000). The fifth trap, Z, is located at 150 m, and was added in November 2003. Details regarding trap operation are found in Benitez-Nelson et al. (2007) and Thunell et al. (2007). Often, the shallowest sediment trap (trap Z) collects less lithogenic material than trap A. Though there are known issues with shallow traps, we believe this supports the idea that most terrigenous material enters the Basin at mid-depth and is laterally supplied from shelf-break INLs, at depths in excess of 150 m.

Most of the sediment transported by the BNL probably remains trapped in the inner to middle portion of the shelf, similar to that of other shelves such as the southern part of Papua New Guinea (Milliman et al., 1999), the Gulf of Riga (Yurkovskis, 2005) and the Texas shelf (Sahl et al., 1987). Nonetheless, some of the material that escapes into the deep basin is likely intercepted by the sediment traps (e.g. Gardner et al., 1983; Biscaye et al., 1994; Walsh and Nittrouer, 1999). Generally, Trap A (~225 m) receives most of the lithogenic material, though closely followed in certain instances by Trap B (~410 m) and Z (~150 m). Trap D (~1200 m) usually records the lowest lithogenic flux (Fig. 7), with the exceptions of July 1997, November 1999 and May 2004. The large increase in terrigenous material observed in 1997 was attributed to an earthquake-induced turbidity flow (Thunell et al., 1999). In 1999 and 2004, increased lithogenic fluxes were caused by elevated precipitation and flooding (Restrepo and Kjerfve, 2000; Lyon, 2003). When small rivers respond to such rainfall events, high quantities of sediment are introduced into the coastal ocean, generating fluid-mud flows and turbidity currents (Mulder and Syvitski, 1995). Hill et al. (2000) reported increased floc size with depth in the Eel River plume during the large 1997 flood. They suggested that the significantly larger discharge allowed flocs to grow as they sank through the plume. Similarly, Ogston et al. (2000) suggested that winter storm-induced freshwater flows increased seaward sediment flow in the same region due to rapid input of sediment combined with the weakening of the density front. We hypothesize that similar conditions occurred in the Cariaco Basin in 1999 and 2004, leading to larger loads of lithogenic material reaching traps A–D. The fact that episodic floods can deliver a large amount of lithogenic material to the deep basin has important implications for the rapid transport and burial of sediments, including terrestrially derived organic carbon (Goldsmith et al., 2008).

In addition to episodic events, sediment traps capture seasonal variations in terrigenous input in the Cariaco Basin (Martinez et al., 2007). During the rainy season, terrigenous fluxes increased, especially in Trap A, suggesting that this trap best reflects changes in the upper water column. Benitez-Nelson et al. (2007) observed similar seasonal increases in PIP, and linked high PIP sediment trap fluxes to episodic riverine inputs; although we did not observe higher PIP concentrations within nepheloid layers once they moved offshore. Sediment trap POC, PN and POP fluxes remain relatively low during the rainy season and only increase slightly with the onset of the upwelling season at the beginning of the year. This suggests that the lithogenic material that reaches the traps during the rainy season is poor in organic matter (Woodworth et al., 2004; Thunell et al., 2007; Goñi et al., 2009), and agrees with the BNL POM data obtained in this study.

Some of the highest average terrigenous and POC fluxes were consistently recorded in May each year (Fig. 7). Spikes in PIP fluxes have also been observed repeatedly during May (Benitez-Nelson et al., 2007). The synchronous increase in POC, PIP and terrigenous material fluxes implies that some of the same processes may be governing the delivery of the material to the traps. May is a transition month, when the Trade Winds weaken and rainfall on the mainland has not yet begun (Fig. 7).

During winter and spring, favorable trade winds promote upwelling and productivity in the Cariaco Basin (Muller-Karger et al., 2001, 2004). The shoreward Ekman transport of dense subtropical underwater (SUW) along the bottom over the shelf would restrict the offshore extension of any bottom nepheloid layers. Thus, terrigenous material, including PIP, would effectively accumulate on the inner shelf. POC produced over the area is in part exported out to the open basin, but a portion of it settles on the shelf. Morales and Ottmann (1961) found that the shelf sediments of the Cariaco Basin were rich in organic matter as a result of the primary production induced by upwelling.

We hypothesize that as the Trade Winds weaken, the dense upwelled water retreats and the sediments stored on the shelf, as well as the freshly deposited autochtonous material, slump offshore together with the BNLs, generating a pulse of POC, PIP and other terrigenous material consistently observed in May. Martinez et al. (2007) observed a spike in the chemical composition (Ti/Al, Fe/Al) of their May trap data, suggesting accumulation of both terrestrially derived material along with biogenic particles derived from upwelling-induced primary production. Similar mobilizations of BNLs have been identified along the Oregon coast (Hales et al., 2006; Perlin et al., 2005), the Portuguese shelf (Oliveira et al., 2002), the Nabimian upwelling system (Inthorn et al., 2006) and the Cretan Sea (Chronis et al., 2000).

Isotopic data indicates that the significant pulse in POC export observed in May in all four traps is of marine origin, yet PIP, trace metal, and lithogenic fluxes clearly suggest that a significant component of the particles are terrestrially derived. We therefore suggest that nepheloid layers, which are enriched in fine-grained sediments, are acting as ballast for the effective transport of autochtonous POC to the deep basin. In essence, the “ballast hypothesis” suggests that mineral ballast (mainly carbonate, opal and lithogenic material) enhances the transport of POC to depth, by increasing POC sinking rates (and hence reducing POC remineralization time), and by providing physical protection from degradation through the interaction between the organic matter and the mineral fraction (Ittekot, 1993; Armstrong et al., 2002; Francois et al., 2002; Klaas and Archer, 2002). In the open ocean, lithogenic material is low and ballast minerals are dominated by calcium carbonate (Francois et al., 2002; Klaas and Archer, 2002). However in coastal areas, the lithogenic fraction increases significantly and can constitute an important component of the mineral ballast (Ittekot, 1993). Thunell et al. (2007) determined that mineral ballast is the single most important factor controlling POC fluxes in the Cariaco Basin. They found a uniform F_{OC}/F_M ratio, suggesting that most POC, including that observed in the shallowest sediment trap (225 m) is associated with ballast material.

Combined, these results underscore the importance of nepheloid layers as a source of terrestrially derived mineral ballast material in the Cariaco Basin. An analogous nepheloid layer/ballast mechanism for NW Africa was suggested by Fischer et al. (2007). Similar to the Cariaco Basin (Thunell et al., 2007), both lithogenic and carbonate components were closely related to POC in NW Africa. Fischer et al. (2007) argued that particles transported offshore through subsurface nepheloid layers provided the necessary ballasting mineral for enhanced POC fluxes, highlighting the significant distances laterally transported particles can travel and the disconnect that may exist between sediment proxies and the overlying water column in certain ocean regions.

5. Conclusions

Subsurface nepheloid layers originating at the mouth of local rivers in the eastern Cariaco Basin are an important mechanism for delivery of terrigenous sediments to the deep basin during the rainy season. This finding highlights the importance of small, local rivers in the Cariaco Basin as primary sources of terrestrial material. Though little studied, these small mountainous rivers have the capacity to deliver large amounts of sediment to the Cariaco Basin, as seen most notably during the 1999 floods. The small size of the mountainous rivers makes them unique recorders of such important, infrequent events that are mitigated in larger rivers with more extensive watersheds. Our results support the hypothesis that other small rivers around the globe may have significant impacts on continental margins, in addition to larger rivers. The small rivers examined here produced BNLs and INLs that appear to effectively transport material from the shelf into the deep basin, providing a lateral supply of terrigenous particles captured by the sediment trap record maintained as part of the CARIACO Oceanographic Time Series Program. The lithogenic material transported by the BNLs and INLs during the rainy season is low in POM, agreeing well with published data. We suggest that the seasonal pulse of sediment to the interior of the Cariaco Basin observed each year is caused by the retention of nepheloid layers on the inner shelf by onshore Ekman transport associated with upwelling. The nepheloid layers are later released as the upwelling subsides in May. The fine sediment of the nepheloid layers may further serve as mineral ballast, enhancing the sinking velocities of POC.

There is still much to be understood regarding subsurface nepheloid layers in the Cariaco Basin, such as their role as a terrigenous carbon source and their seasonal patterns. Information is also needed on INLs and their potential sediment contribution to the Manzanares Submarine Canyon, which directly funnels terrigenous sediment from the shelf to deep waters. Nonetheless, these initial observations provide a preliminary understanding of the alternating influence of coastal upwelling and riverine inputs to particles settling at the bottom of the basin and highlight the importance of subsurface nepheloid layers in lateral particle transport and deposition.

The nepheloid layers associated with the small mountainous rivers in the Cariaco Basin have the capacity of delivering large amounts of lithogenic material to the deep, which has important implications for the rapid transport and burial of sediments, including terrestrially derived organic carbon. However, during the last 30 years, anthropogenic influences on the small rivers around the Basin have significantly altered the drainage and sediment load, yet reliable data to quantify the level of influence and change over time are not available. We need a better understanding of the natural variability of these fluvial systems, trends and impact of episodic events, to better elucidate future conditions in the region.

Acknowledgements

The authors wish to thank the crew of the *R/V Hermano Ginés* and the personnel working for the CARIACO Program at Fundación La Salle, EDIMAR, in particular Aitzol Arrellano, Laurencia Guzmán and Jesús Narváez. We also thank the staff of the Paleolab at the College of Marine Science (USF) for their help analyzing part of the samples, in particular Ethan Goddard, Elon Malkin, Greg Ellis and Ana Hoare. The manuscript was greatly improved by the thoughtful comments of three anonymous reviewers. This work was supported by the National Science Foundation (Grant OCE-0326268) and the Fondo Nacional de Investigaciones Científicas y Tecnológicas (FONACIT, Venezuela, Grant 96280221). This is the Institute of Marine Remote Sensing (IMaRS) contribution #134.

References

Alvera-Azcárate, A., Barth, A., Weisberg, R., 2008. A nested model of the Cariaco Basin (Venezuela): description of the basin's interior hydrography and interactions with the open ocean. Ocean Dyn.

Andressen, R., Pulwarty, R., 2001. Análisis de las lluvias excepcionales causantes de la tragedia del Estado Vargas, Venezuela, en diciembre de 1999. IV Simposio Internacional de Desarrollo Sustentable en Los Andes, 25 noviembre–2 diciembre, 2001, Mérida, Venezuela.

Armstrong, R.A., Lee, C., Hedges, J.I., Honjo, S., Wakeham, S.G., 2002. A new, mechanistic model for organic carbon fluxes in the ocean based on the quantitative association of POC with ballast minerals. Deep-Sea Res. Part II 49, 219–236.

Astor, Y., Meri, J., Muller Karger, F., 1998. Variabilidad estacional hidrográfica en la Fosa de Cariaco. Mem. Soc. Cienc. Nat. La Salle 63 (149), 61–72.

Azetsu-Scott, K., Johnson, B.D., Petrie, B., 1995. An intermittent, intermediate nepheloid layer in Emerald Basin. Scotian Shelf. Cont. Shelf Res. 15 (2–3), 281–293.

Black, D., Abahazi, M.A., Thunell, R.C., Kaplan, A., Tappa, E.J., Peterson, L.C., 2007. An 8-century tropical Atlantic SST record from the Cariaco Basin: baseline variability, twentieth-century warming, and Atlantic hurricane frequency. Paleoceanography 22, PA4204.

Behrenfeld, M., Boss, E., 2003. The beam attenuation to chlorophyll ratio: an optical index of phytoplankton physiology in the surface ocean? Deep-Sea Res. I 50, 1537–1549.

Benitez-Nelson, C., O'Neill, L.P., Styles, R.M., Thunell, R.C., Astor, Y., 2007. Inorganic and organic sinking particulate phosphorus fluxes across the oxic/anoxic water column of Cariaco Basin. Venez. Mar. Chem. 105, 90–100.

Biscaye, P.E., Flagg, C.N., Falkowski, P.G., 1994. The shelf edge exchange processes experiment, SEEP-II an introduction to hypotheses, results and conclusions. Deep-Sea Res. 41, 231–252.

Boss, E., Twardowski, M.S., Herring, S., 2001. Shape of the particulate beam attenuation spectrum and its inversion to obtain the shape of the particulate size distribution. Appl. Opt. 40, 4885–4893.

Brunskill, G.J., 2009. An overview of tropical margins. In: Liu, K.-K., et al. (Eds.), Carbon and Nutrient Fluxes in Continental Margins, Global Change—The IGBP Series, p. 423.

Chronis, G., Lykousis, V., Georgopoulos, D., Zervakis, V., Stavrakakis, S., Poulos, S., 2000. Suspended particulate matter and nepheloid layers over the southern margin of the Cretan Sea (N.E. Mediterranean): seasonal distribution and dynamics. Prog. Oceanogr. 46, 163–185.

Curran, K.J., Hill, P.S., Milligan, T.G., 2002. Fine-grained suspended sediment dynamics in the Eel River flood plume. Cont. Shelf Res. 22, 2537–2550.

Dickson, R.R., McCave, I.N., 1986. Nepheloid layers on the continental slope west of Porcupine Bank. Deep-Sea Res. 33, 791–818.

Dickson, A.G., Sabine, C.L., Christian, J.R. (Eds.), 2007. Guide to best practices for ocean CO_2 measurements. PICES Special Publication 3, 191pp.

Elmore, A.C., Thunell, R.C., Styles, R., Black, D., Murray, R.W., Martinez, N., Astor, Y., 2009. Quantifying the seasonal variations in fluvial and eolian sources of terrigenous material to Cariaco Basin. Venez. J. S. Am. Earth Sci. 27, 197–210. doi:10.1016/j.jsames.2008.11.002.

Fischer, G., Karakas, G., Blaas, M., Ratmeyer, V., Nowald, N., Schlitzer, R., Helmke, P., Davenport, R., Donner, B., Neuer, S., Wefer, G., 2007. Mineral ballast and particle settling rates in the coastal upwelling system off NW Africa and the South Atlantic. Int. J. Earth Sci.

Francois, R., Honjo, S., Krishfield, R., Manganini, S., 2002. Factors controlling the flux of organic carbon to the bathypelagic zone of the ocean. Global Biogeochem. Cycles 16 (4), 1087.

Gardner, W.D., Richardson, M.J., Hinga, K.R., Biscaye, P.E., 1983. Resuspension measured with sediment traps in a high-energy environment. Earth Planet. Sci. Lett. 66, 262–278.

Gardner, W.D., 1989. Baltimore Canyon as a modern conduit of sediment to the deep sea. Deep-Sea Res. 36 (3), 323–358.

Goldsmith, S., Carey, A., Berry Lyons, W., Kao, S.-J., Lee, T.-Y., Chen, J., 2008. Extreme storm events, landscape denudation, and carbon sequestration: Typhoon Mindulle, Choshui River, Taiwan. Geology 36 (6), 483–486.

Goñi, M.A., Ruttenberg, K.C., Eglinton, T.I., 1997. Source and contribution of terrigenous organic carbon to surface sediments in the Gulf of Mexico. Nature 389 (6648), 275–278.

Goñi, M.A., Monacci, N., Gisewhite, R., Crockett, J., Nittrouer, C., Ogston, A., Alin, S.R., Aalto, R., 2008. Terrigenous organic matter in sediments from the Fly River Delta (Papua New Guinea). J. Geophys. Res. 113, F01S10.

Goñi, M.A., Aceves, H., Benitez-Nelson, B., Tappa, E., Thunell, R., Black, D.E., Muller-Karger, F., Astor, Y., Varela, R., 2009. Oceanographic and climatologic controls on the compositions and fluxes of biogenic materials in the water column and sediments of the Cariaco Basin over the Late Holocene. Deep-Sea Res. I.

Hales, B., Karp-Boss, L., Perlin, A., Wheeler, P.A., 2006. Oxygen production and carbon sequestration in an upwelling coastal margin. Global Biogeochem. Cycles 20, GB3001.

Hedges, J.I., Keil, R.G., 1995. Sedimentary organic matter preservation: an assessment and speculative synthesis. Mar. Chem. 49, 81–115.

Hickey, B.M., Baker, E., Kachel, N.B., 1986. Suspended particle movement in and around Quinault Submarine Canyon. Mar. Geol. 71, 35–83.

Hicks, D.M., Gomez, B., Trustrum, N.A., 2004. Event suspended sediment characteristics and the generation of hyperpycnal plumes at river mouths: east coast continental margin, North Island, New Zealand. J. Geol. 112, 471–485.

Hill, P.S., Milligan, T.G., Geyer, W.R., 2000. Controls on effective settling velocity of suspended sediment in the Eel River flood plume. Cont. Shelf Res. 20, 2095–2111.

Hughen, K.A., Overpeck, J.T., Peterson, L.C., Anderson, R.F., 1996. The nature of varved sedimentation in the Cariaco Basin, Venezuela, and its paleoclimatic significance. In: Laminated Sediments, A.E.S. (Ed.), Palaeoclimatology and Palaeoceanography, Geological Society Special Publication No. 116, pp. 171–183.

Hung, J.-J., Chan, C.-L., Gong, G.-C., 2007. Summer distribution and geochemical composition of suspended-particulate matter in the East China Sea. J. Oceanogr. 65, 189–202.

INIA-MARN, 2003. Establecimiento del equilibrio ecológico en las lagunas de Píritu y Unare: Comportamiento Hidráulico. Online document: 〈http://es.mayeticvillage.com/QuickPlace/unare2/Main.nsf/h_Index/0A0DD2E94438EA90C1256E650082FF99/?OpenDocument〉.

Inman, D.L., Jenkins, S.A., 1999. Climatic change and the episodicity of sediment flux of small California rivers. J. Geol. 107, 251–270.

Inthorn, M., Mohrholz, V., Zabelc, M., 2006. Nepheloid layer distribution in the Benguela upwelling area offshore Namibia. Deep-Sea Res. I 53, 1423–1438.

Ittekot, V., 1993. The abiotically driven biological pump in the ocean and short term fluctuations in atmospheric CO_2 contents. Global Planet Change 8, 17–25.

Kao, S.-J., Shiah, F.-K., Wang, C.-H., Liu, K.-K., 2006. Efficient trapping of organic carbon in sediments on the continental margin with high fluvial sediment input off southwestern Taiwan. Cont. Shelf Res. 26, 2520–2537.

Karp-Boss, L., Wheeler, P.A., Hales, B., Covert, P., 2004. Distributions and variability of particulate organic matter in a coastal upwelling system. J. Geophys. Res. 109, C09010.

Kineke, G.C., Woolfe, K.J., Kuehl, S.A., Milliman, J.D., Dellapenna, T.M., Purdon, R.G., 2000. Sediment export from the Sepik River, Papua New Guinea: evidence for a divergent sediment plume. Cont. Shelf Res. 20, 2239–2266.

Klaas, C., Archer, D.E., 2002. Association of sinking organic matter with various types of mineral ballast in the deep sea: implications for the rain ratio. Global Biogeochem. Cycles 16 (4), 1116.

Lentz, S.J., Trowbridge, J.H., 1991. The bottom boundary layer over the northern California shelf. J. Phys. Oceanogr. 21, 1186–1201.

Lorenzoni, L., Benitez-Nelson, C., Thunell, R.C., Hollander, D., Varela, R., Astor, Y., Muller-Karger, F.E., Earthquake-driven sediment transport down a submarine canyon in the Cariaco Basin, Venezuela. Geology, submitted for publication.

Lyon, B., 2003. Enhanced seasonal rainfall in Northern Venezuela and the extreme events of December 1999. J. Climate 16, 2302–2306.

Martinez, N.C., Murray, R.W., Thunell, R.C., Peterson, L.C., Muller-Karger, F., Astor, Y., Varela, R., 2007. Modern climate forcing of terrigenous deposition in the tropics (Cariaco Basin, Venezuela). Earth Planet. Sci. Lett. 264, 438–451.

McCave, I.N., Hall, I.R., 2002. Turbidity of waters over the Northwest Iberian continental margin. Prog. Oceanogr. 52 (2–4), 299–313.

McCave, I.N., Hall, I.R., Antia, A.N., Chou, L., Dehairs, F., Lampitt, R.S., Thomsen, L., van Weering, T.C.E., Wollast, R., 2001. Distribution, composition and flux of particulate material over the European margin at 47°50′N. Deep-Sea Res. II 48, 3107–3139.

McPhee-Shaw, E.E., Sternberg, R.W., Mullenbach, B., Ogston, A.S., 2004. Observations of intermediate nepheloid layers on the northern California continental margin. Cont. Shelf Res. 24 (6), 693–720.

McPhee-Shaw, E.E., 2006. Boundary–interior exchange: reviewing the idea that internal-wave mixing enhances lateral dispersal near continental margins. Deep-Sea Res. II 53, 42–59.

Milliman, J.D., Farnsworth, K.M., Albertin, C., 1999. Flux and fate of fluvial sediments leaving large islands in the East Indies. J. Sea Res. 41, 97–107.

Milliman, J.D., Syvistski, J.P.M., 1992. Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers. J. Geol. 100, 525–544.

Ministerio del Poder Popular para el Ambiente (MINAMB). 〈http://www.minamb.gob.ve/〉.

Morales, P.R., Ottmann, F., 1961. Primer estudio topográfico y geológico del Golfo de Cariaco. Bol. Inst. Oceanogr. Univ. Oriente 1 (1), 5–20.

Morelock, J., Maloney, N.J., Bryant, W.R., 1972. Structure and sediments of the continental shelf of Central Venezuela. Bol. Inst. Oceanogr. Univ. Oriente 11, 127–136.

Mulder, T., Syvitski, J.P.M., 1995. Turbidity currents generated at river mouths during exceptional discharges to the world oceans. J. Geol. 103, 285–299.

Muller-Karger, F.E., Varela, R., Thunell, R., Astor, Y., Zhang, H., Hu, C., 2004. Processes of coastal upwelling and carbon flux in the Cariaco Basin. Deep-Sea Res. II. Special Issue: Views of Ocean Processes from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) Mission: vol. 2—Edited by D.A. Siegel, A.C. Thomas and J. Marra, vol. 51/10–11, pp. 927–943.

Muller-Karger, F.E., Varela, R., Thunell, R., Scranton, M., Bohrer, R., Taylor, G., Capelo, J., Astor, Y., Tappa, E., Ho, T.Y., Walsh, J.J., 2001. Annual cycle of primary production in the Cariaco Basin: response to upwelling and implications for vertical export. J. Geophys. Res. 106 (C3), 4527–4542.

Ogston, A.S., Cacchione, D.A., Sternberg, R.W., Kineke, G.C., 2000. Observations of storm and river flood-driven sediment transport on the northern California continental shelf. Cont. Shelf Res. 20, 2141–2162.

Oliveira, A., Vitorino, J., Rodrigues, A., Jouanneau, J.M., Dias, J.A., Weber, O., 2002. Nepheloid layer dynamics in the northern Portuguese shelf. Progr. Oceanogr. 52 (2–4), 195–213.

Pak, H., Zaneveld, J.R.V., Kitchen, J., 1980. Intermediate nepheloid layers observed off Oregon and Washington. J. Geophys. Res. 85 (C11), 6697–6708.

PDVSA, 1992. Imagen de Venezuela, una visión espacial, second ed., Petróleos de Venezuela, S.A. Caracas, Venezuela.

Perlin, A., Moum, J.N., Klymak, J.M., 2005. Response of the bottom boundary layer over a sloping shelf to variations in alongshore wind. J. Geophys. Res. 110, C10S09.

Peterson, L.C., Haug, G.H., 2006. Variability in the mean latitude of the Atlantic Intertropical Convergence Zone as recorded by riverine input of sediments to the Cariaco Basin (Venezuela). Palaeogeogr. Palaeoclimatol. Palaeoecol. 234 (1), 97–113.

Peterson, L., Haug, G., Hughen, K., Rohl, U., 2000. Rapid changes in the hydrologic cycle of the tropical Atlantic during the last glacial. Science 290, 1947–1951.

Puig, P., Palanques, A., 1998. Nepheloid structure and hydrographic control on the Barcelona continental margin, northwestern Mediterranean. Mar. Geol. 149 (1–4), 39–54.

Puig, P., Ogston, A.S., Mullenbach, B.L., Nittrouer, C.A., Sternberg, R.W., 2003. Shelf-to-canyon sediment-transport processes on the Eel continental margin (northern California). Mar. Geol. 193 (1–2), 129–149.

Restrepo, J.D., Kjerfve, B., 2000. Magdalena River: interannual variability (1975–1995) and revised water discharge and sediment load estimates. J. Hydrol. 235, 137–149.

Sahl, L.E., Merrell, W.J., McGrail, D.W., Webb, J.A., 1987. Transport of mud on continental shelves; evidence from the Texas shelf. Mar. Geol. 76 (1/2), 33–43.

Schubert, C., 1982. Origin of the Cariaco Basin, Southern Caribbean Sea. Mar. Geol. 47, 345–360.

Thompson, R.E., Fine, I.V., 2003. Estimating mixed layer depth from oceanic profile data. J. Atmos. Oceanic Technol. 20, 319–329.

Thunell, R., Varela, R., Llano, M., Collister, J., Muller-Karger, F., Bohrer, R., 2000. Organic carbon flux in an anoxic water column: sediment trap results from the Cariaco Basin. Limnol. Oceanogr. 45, 300–308.

Thunell, R., Tappa, E., Varela, R., Llano, M., Astor, Y., Muller-Karger, F., Bohrer, R., 1999. Increased marine sediment suspension and fluxes following an earthquake. Nature 398, 233–236.

Thunell, R., Benitez-Nelson, C., Varela, R., Astor, Y., Müller-Karger, F., 2007. Particulate organic carbon fluxes along upwelling-dominated continental margins: rates and mechanisms. Global Biogeochem. Cycles 21, GB1022.

Trowbridge, J.H., Butman, B., Limeburner, R., 1994. Characteristics of the near-bottom suspended sediment field over the continental shelf off northern California based on optical attenuation measurements during STRESS and SMILE. Cont. Shelf Res. 14 (10–11), 1257–1272.

Virmani, J., Weisberg, R., 2009. Fish affects on ocean current observations in the Cariaco Basin. J. Geophys. Res. 114, C03028.

Walsh, J.P., Nittrouer, C.A., 1999. Observations of sediment flux on the Eel continental slope, northern California. Mar. Geol. 154, 55–68.

Werne, J.P., Hollander, D.J., 2004. Balancing supply and demand: controls on carbon isotope fractionation in the Cariaco Basin (Venezuela) Younger Dryas to Present. Mar. Chem. 92 (1–4), 275–293.

Wheatcroft, R.A., 2000. Oceanic flood sedimentation: a new perspective. Cont. Shelf Res. 20, 2059–2066.

Woodworth, M., Goñi, M.A., Tappa, E., Tedesco, K., Thunell, R., Astor, Y., Varela, R., Díaz-Ramos, J.R., Müller-Karger, F., 2004. Oceanographic controls on the carbon isotopic compositions of sinking particles from the Cariaco Basin. Deep-Sea Res. I 51, 1955–1974.

Yurkovskis, A., 2005. Seasonal benthic nepheloid layer in the Gulf of Riga, Baltic Sea: sources, structure and geochemical interactions. Cont. Shelf Res. 25, 2182–2195.

Zinck, A., 1977. Ríos de Venezuela. Cuadernos Lagoven, Caracas, 63p.