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Carbon and biogenic silica export influenced by the Amazon River Plume: Patterns of remineralization in deep-sea sediments

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ABSTRACT

The Amazon River Plume delivers freshwater and nutrients to an otherwise oligotrophic western tropical North Atlantic (WTNA) Ocean. Plume waters create conditions favorable for carbon and nitrogen fixation, and blooms of diatoms and their diazotrophic cyanobacterial symbionts have been credited with significant CO_2 uptake from the atmosphere. The fate of the carbon, however, has been measured previously by just a few moored or drifting sediment traps, allowing only speculation about the full extent of the plume′s impact on carbon flux to the deep sea. Here, we used surface (0.5 m) sediment cores collected throughout the Demerara Slope and Abyssal Plain, at depths ranging from 1800 to 5000 m, to document benthic diagenetic processes indicative of carbon flux. Pore waters were extracted from sediments using both mm- and cm-scale extraction techniques. Profiles of nitrate (NO_3) and silicate ($Si(OH)_4$) were modeled with a diffusion-reaction equation to determine particulate organic carbon (POC) degradation and biogenic silica (bSi) remineralization rates. Model output was used to determine the spatial patterns of POC and bSi arrival at the sea floor. Our estimates of POC and Si remineralization fluxes ranged from 0.16 to 1.92 and 0.14 to 1.35 mmol m^{-2} d^{-1}, respectively. A distinct axis of POC and bSi deposition on the deep sea floor aligned with the NW axis of the plume during peak springtime flood. POC flux showed a gradient along this axis with highest fluxes closest to the river mouth. bSi had a more diffuse zone of deposition and remineralization. The impact of the Amazon plume on benthic fluxes can be detected northward to 10°N and eastward to 47°W, indicating a footprint of nearly 1 million km^2. We estimate that 0.15 Tmol C y^{-1} is remineralized in abyssal sediments underlying waters influenced by the Amazon River. This constitutes a relatively high fraction (~7%) of the estimated *C* export from the region.; the plume thus has a demonstrable impact on C_{org} export in the western Atlantic. Benthic fluxes under the plume were comparable to and in some cases greater than those observed in the eastern equatorial Atlantic, the southeastern Atlantic, and the Southern Ocean.

1. Introduction

Rivers impact the production of carbon in the ocean by providing a source of nutrients as well as trace elements and stratification that can enhance primary production, resulting in net carbon transport from the atmosphere to the deep sea (Eppley and Peterson, 1979; Raymond and Cole, 2003; Smith and Hitchcock, 1994). The Amazon River is responsible for one fifth of the total riverine discharge to the world oceans (Gibbs, 1972), delivering freshwater at a seasonally-variable rate of 120,000–300,000 m^3 s^{-1} (Cooley et al., 2007; Perry et al., 1996). Although this freshwater mixes with ocean water, a plume of lower salinity waters and CDOM can be traced northwest to the Caribbean in the late spring during periods of maximum discharge as well as eastward into the North Atlantic due to the seasonal retroflection of the North Brazil Current (NBC) in the fall (Del Vecchio and Subramaniam, 2004; Froelich et al., 1978; Johns et al., 1998; Muller-Karger et al., 1988, 1995).

Although the tropical North Atlantic is generally considered to be a net source of CO_2 to the atmosphere (Deuser et al., 1988; Mikaloff Fletcher et al., 2007; Takahashi et al., 2002), CO_2 uptake has been observed in the region influenced by the Amazon River Plume (Cooley et al., 2007; Cooley and Yager, 2006; Ternon et al., 2000). Subramaniam et al. (2008) hypothesized that the plume supports ecological niches in mesohaline waters (30 < sea surface salinity (SSS) < 35) where surface waters are depleted in N but contain a relative

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excess of dissolved Si and P (Shipe et al., 2006; Subramaniam et al., 2008). This combination creates optimal conditions for diatom–diazotroph associations (DDAs), which have been suggested to be an important vector for carbon sequestration and export in this region (Carpenter et al., 1999; Foster et al., 2007; Subramaniam et al., 2008). Recently, Yeung et al. (2012) confirmed that DDA blooms increase carbon export efficiency; however, it is unclear if the blooms also result in an increase in the material reaching the deep ocean. Floating sediment traps deployed at 150 m (Subramaniam et al., 2008) showed a correlation between the presence of DDAs in the water column and mass flux, but this does not tell us how much carbon reaches the sea floor. A moored trap deployed at 3200 m at 13.22°N, 41.68°E (Deuser et al., 1988), showed a relationship between higher primary productivity and higher particle flux, but it is unknown if DDAs were responsible for the blooms. We have adopted the approach of using the sediments as 'the ultimate sediment trap' (Herman et al., 2001; Jahnke, 1990; Reimers et al., 1992) to map and quantify the export of carbon and biogenic Si to the deep sea in the area of the WTNA influenced by the Amazon Plume. Although only a small fraction of the C and bSi exported from surface waters reaches the sea floor at 4500 m, in the absence of significant sediment redistribution (focusing), there should be a benthic signal of C input that relates to production and export.

The majority of work on marine sediments and particulate organic matter in the area of the Amazon Plume has been limited to the river mouth and the adjacent continental shelf (Aller and Blair, 2006; Aller et al., 1998, 2004; Blair et al., 2004; Druffel, 2005; Hedges et al., 1986; Keil et al., 1997; Kineke et al., 1996; Kuehl et al., 1986, 1996; Nittrouer and DeMaster, 1996). Our work includes sites 500–1200 km from the Amazon River mouth and focuses primarily on deep-sea (> 3500 m) sites in the open ocean. Pore water studies on deep-sea sediments from the Amazon Fan (Kasten et al., 1998, 2003; Schlünz et al., 1999; Schulz et al., 1994) and the Ceara Rise (Martin and Sayles, 1996, 2006; Wenzhöfer and Glud, 2002) serve as an excellent reference to our study insofar as today these areas are subject to little direct influence from the river plume.

For many open ocean environments, the organic matter reaching the sea floor is nearly completely remineralized during early diagenesis (Bender and Heggie, 1984; Burdige, 2007; Canfield, 1994; Hedges and Keil, 1995; Premuzic et al., 1982), hence the oxidation flux should closely approximate the deposition flux. We measured and modeled pore water NO_3^- profiles and interpreted their shape as a proxy for oxygen utilization and carbon oxidation (Goloway and Bender, 1982; Martin et al., 1991; Martin and Sayles, 1996, 2006). This approach has a benefit over measurements of oxygen gradients, which are sometimes subject to artifacts due to core recovery (Wenzhöfer et al., 2001). Nitrate profiles, as a proxy of carbon remineralization, are indicative of where deposition is occurring and we compare this 'footprint' to the location of the river plume in the surface ocean. We also calculate the flux of dissolved Si to provide an indication of the importance of biogenic silica export throughout the region.

2. Study area and methods

We present data from the ANACONDAS (Amazon iNfluence on the Atlantic: CarbOn export from Nitrogen fixation by DiAtom Symbioses) project, which consisted of three cruises throughout the WTNA aboard the *R/V Knorr* (May–June 2010), the *R/V Melville* (September–October 2011), and the *R/V Atlantis* (July 2012). We collected sediment cores from 1800–5044 m at 32 sites across the Demerara Slope/Abyssal Plain (Fig. 1), using a multi-corer with 9.8 cm (ID) diameter core tubes (Barnett et al., 1984) (Table 1). Immediately after

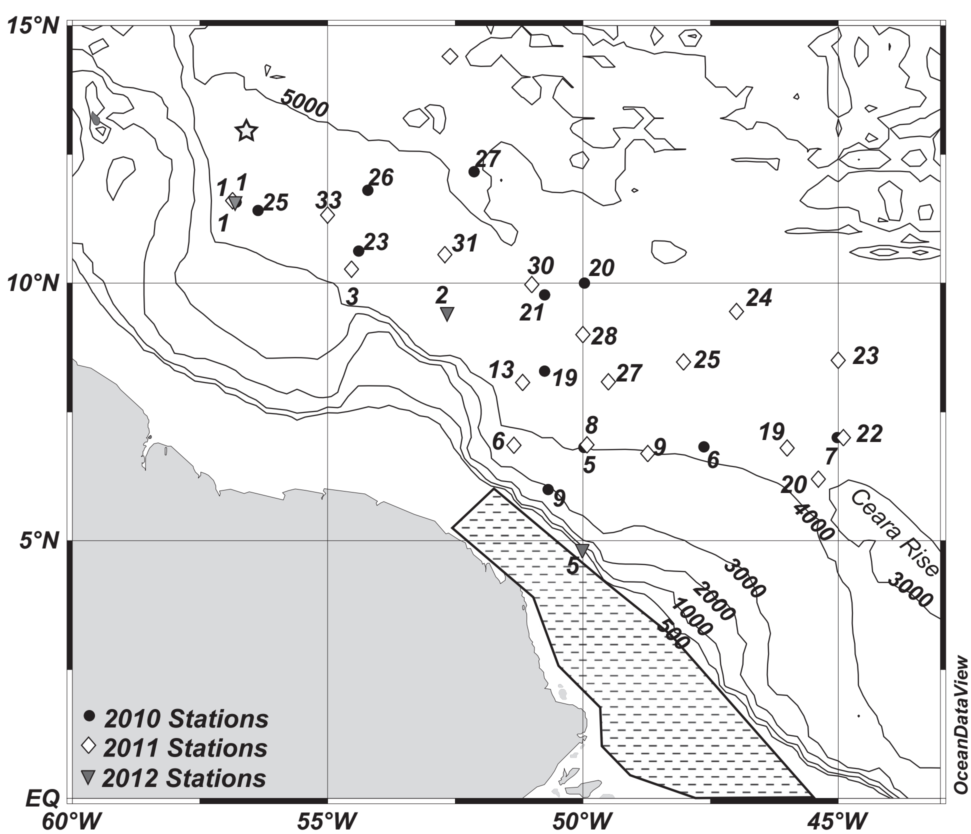

Fig. 1. Map of study area. Circles represent stations from the 2010 cruise, diamonds from 2011, triangles from 2012. Depth contours (m). The Amazon River mouth is at 0°N 50°W. The star indicates the location of a moored sediment trap array from the previous work (Deuser et al., 1988). The shaded shelf area indicates the study region of the AmaSeds project (Nittrouer and DeMaster, 1996).