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Amazon water lenses and the influence of the North Brazil Current on the continental shelf

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ABSTRACT

The exchange processes on the Amazon continental shelf in northern Brazil are subject to complex interactions that involve forcings derived from distinct sources. The Amazon shelf is a unique and highly dynamic environment in which considerable discharge of freshwater enters the Atlantic Ocean, producing extensive *Amazon Water Lenses* (AWL). In addition to the presence of the AWL, the shelf is influenced by the semidiurnal oscillations of the tides and the strong North Brazil Current (NBC), a boundary current of the western Atlantic. The present study was based primarily on the influence of the freshwater input and the NBC on the shelf and the Amazon Shelf Break (ASB) off the mouth of the Pará River. For this purpose, hydrographic and hydrodynamic data were obtained by moorings of the AMANDES Project (April–July 2008), located on the Amazon shelf and the ASB. Spectral analysis and the continuous wavelet transform were applied to define tidal (high frequency/short period) and subtidal (low frequency/long period) signals. The results indicated that on both the shelf and the break, the semidiurnal tides are responsible for the residual landward transport and are predominantly *across-shelf*. Low-frequency motions in the synoptic bands and the AWL are related to spatial changes in the velocity field, mainly on the ASB in the *along-shelf* direction. The flow of the NBC can be interpreted as an *along-shelf* low-frequency oscillation capable of altering the spatial configuration of the velocity field, although its influence is perceived only in the absence of the AWL.

1. Introduction

The Amazon continental shelf is located in northern Brazil (Fig. 1) and extends more than 250 km into the Atlantic Ocean, reaching the shelf break at the 100 m isobath (Nittrouer and DeMaster, 1996). This is a unique and extremely dynamic environment dominated by the interactions of a number of different physical forcings, including tidal currents (Beardsley et al., 1995), the input of freshwater and the variation in the estuarine plume (Lentz, 1995; Lentz and Limeburner, 1995), and the North Brazil Current (NBC), which flows along the Amazon Shelf Break, or ASB (Johns et al., 1998). These forcings vary considerably over time and in space, primarily due to oscillations in wind conditions, which are influenced primarily by the northeasterly (December–May) and southeasterly (June–November) trade winds.

The Amazon basin is the world's largest river basin (Nittrouer and DeMaster, 1996), with an area of approximately 7×10^5 km^2, which extends from the Andes mountains, passing through the Amazon forest to its estuary in the Atlantic Ocean. The Amazon also has the highest net discharge of any river, with an annual mean discharge of 0.8×10^5 m^3 s^{-1} and maximum values of approximately 2.4×10^5 m^3 s^{-1}, accounting for approximately 20% of the total amount of freshwater transported to oceans around the world (Oltman, 1968; Dai and Trenberth, 2002). The Pará River, which joins the Amazon at its mouth, is a second major body of freshwater in the basin, with a discharge of approximately 10^4 m^3 s^{-1} (Prestes et al., 2014). The magnitude of this continental input results in an extensive system of *Amazon Water Lenses* (AWL), generating complex micromesoscale processes that influence both boundary and mixed-layer patterns (Silva et al., 2005). This freshwater discharge is only weakly correlated with variations in saline intrusions, as the effect of astronomic tides is the most relevant aspect of the dynamics of the saline front (Molinas et al., 2014). The tidal effect is the principal forcing influencing the Amazon continental shelf (Beardsley et al., 1995; Geyer et al., 1996; Gabioux et al., 2005; Le Bars et al., 2010), with strong oscillations of semidiurnal, diurnal, and fortnightly tidal frequencies. During spring tides, barotropic tidal currents reach maximum instantaneous values of 2.0 m s^{-1}, decreasing to less than 0.8 m s^{-1} during neap tides (Geyer et al., 1996).

The NBC is another major local forcing on both the shelf and the

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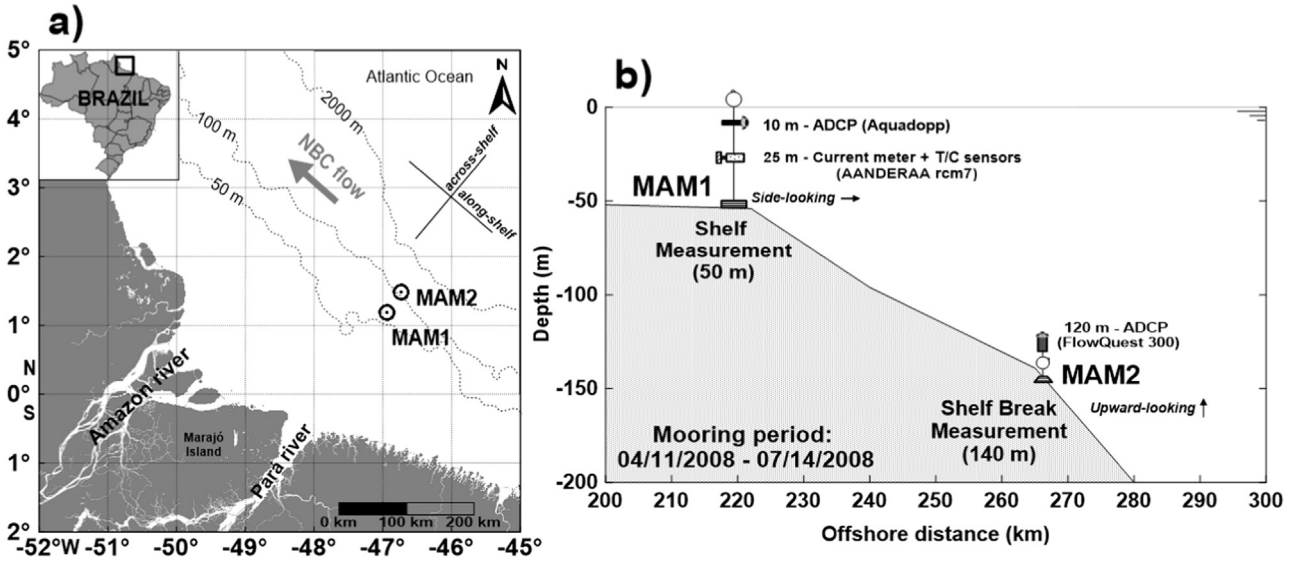

Fig. 1. Study area showing the two AMANDES moorings; a) map of the study area in northern Brazil, showing some adjacent river basins, the predominant direction of the NBC on the continental shelf and isobath lines indicating the shelf and ASB environments; b) Diagram of the MAM1 and MAM2 moorings on the shelf and ASB, respectively, highlighting the mooring instrumentation and monitoring period, as well as depth measurement and the distance from the coast.

ASB. The NBC is a strong western boundary current that plays an important role in the predominantly northwestward flow along the continental slope (Johns et al., 1998; Silva et al., 2009). This current originates at the southern and central bifurcations of the South Equatorial Current and is associated with the North Brazil Undercurrent (NBUC); together, these currents form the NBC/NBUC system. At 44°W, the NBC/NBUC system transports approximately 35 Sv (1 Sv = 10^6 m^3 s^{-1}) with a seasonal variation of ± 3 Sv toward the equator (Johns et al., 1998; Bourlès et al., 1999). The NBC flows to the northwest along the Amazon Shelf Break at velocities of approximately 1.0 ms^{-1} (Bourlès et al., 1999; Neto and Silva, 2013), with a mean transport of 26 Sv, reaching a maximum of 36 Sv in July–August and a minimum of 13 Sv in April–May (Johns et al., 1998).

While this system is influenced by a wide range of physical forcings, the present study primarily investigated the influence of the freshwater input and the NBC on the shelf and the ASB off the mouth of the Pará River. In this context, the term "*Amazon Water Lenses*" (AWL) refers specifically to the presence of freshwater derived from the continental input of the Amazon and Pará rivers at distances of up to 200 km offshore. The study is based on the analysis of hydrodynamic and hydrographic data from two moorings deployed during the AMANDES (AMAzone ANDES) Project. The measurement points are located on the Amazon shelf directly off the mouth of the Pará River, at a distance of approximately 250 km from the coast.

The overall purpose of the AMANDES Project was to better understand the physical and chemical fluxes, including those of geochemical tracers, from the continents to the oceans. The AMANDES Project specifically focused on the physicochemical exchange in the Amazon estuary and shelf system and its impact on the water masses of the adjacent Atlantic Ocean (Le Bars et al., 2010). The present study compared the prevalence and variability of the physical forcings outlined above between the continental shelf and the ASB in an attempt to resolve major oceanographic questions, such as whether the tidal effects and the influence of the AWL observed on the relatively shallow shelf are also prevalent at the deeper ASB. Our hypothesis is that the NBC also influences the main body of the continental shelf (onshore from the ASB) during those periods when its flow is most intense. Measurements of the NBC taken along the ASB during the transition period between its lowest and highest intensities could help to test this hypothesis. These analyses are unprecedented as they describe the ASB dynamics at a novel locality (approximately 1° N and 46.5° W) off the mouth of the Pará River.

Velocity time series were analyzed by a low-pass filter to identify the signal prevalence in the frequency domain. The vertical differences in the velocity spectrum were also investigated by applying the fast Fourier transform (FFT) and the continuous wavelet transform, or CWT (Percival and Walden, 1993; Torrence and Compo, 1998; Labat, 2005; Sassi and Hoitink, 2013; Briciu, 2014; Mahanty et al., 2015). The Richardson number (*Ri*) was also calculated to verify the relationship between the turbulent and laminar flows and the low- and high-frequency oscillations, given that shifts in the velocity field determine the characteristics of the stratification and mixing patterns. These analyses help to better understand whether the prevalent physical processes of the continental shelf also dominate the ASB.

The rest of this paper is organized into four main sections. The study area and methods for the hydrographic and hydrodynamic analyses are described in Section 2. Section 3 presents the results of the temporal series from the two moorings, the low-pass filter and signal analysis of the velocity time series (Sections 3.4 and 3.5), and the Richardson number (Section 3.6). The influence of the AWL, tides, and NBC on the shelf and the ASB are discussed in Section 4, focusing on their spatio-temporal variations. Conclusions are presented in Section 5.

2. Methods

2.1. Study area and data acquisition

The study area comprises the Amazon continental shelf and the ASB, which are subject to the continental input of the Amazon and Pará rivers into the western equatorial Atlantic Ocean (latitude: 1–2°N; longitude: 46–48°W) (Fig. 1a). Two of four 15–day oceanographic expeditions to the Amazon shelf on the R/V Antea (AMANDES III, part of the AMANDES Project) were used to deploy oceanographic moorings (as described below) and collect samples of the water column during different seasons (April 2008 and July 2008). The moorings were deployed for over three months, between 4/11/2008 and 7/14/2008 (Table 1).

2.1.1. Mooring I (MAM1 – shelf measurement)

At the 50 m isobath, an acoustic Doppler current profiler (ADCP) was moored at a depth of 10 m, and a current meter and conductivity-temperature data loggers were moored at a depth of 25 m (Fig. 1b). The