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Dynamics of the Saline Front in the Northern Channel of the Amazon River – Influence of Fluvial Flow and Tidal Range (Brazil)

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ABSTRACT

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Part of the BARRANORTE project, this study analyzes the dynamics of saline intrusion in the Northern Channel of the Amazon River (0°50'N-1°50'N, 48°50'W-50°W). Monitoring the saline wedge helps locate regions with large deposits of sediment and contributes to the improvement of navigational and safety aids and environmental monitoring. Two campaigns were carried out in this study, in June 2006 (maximum fluvial discharge) and July 2007. Data were collected at six stations in 2006 and eleven in 2007, with 12 hours of measurements and a vertical profile taken every hour, covering half a tidal cycle. River flow and tidal data were obtained from the National Water Agency and Brazilian Navy, respectively. Surface winds were estimated using the QuikSCAT(NASA) scatterometer. The variation in the position of the saline wedge in the Northern Channel indicates significant variation on both a seasonal and a tidal cycle. The saline wedge was located 80 km from the mouth of the channel in minimal discharge conditions (data from the AMASSEDS project) and up to 120 km at maximum discharge (present study). Differences in this distance between 2006 (106 km) and 2007 (120 km) were probably related to those in the tidal regime, with data being collected during the neap tide in 2006 (H=2.4 m) and spring tide in 2007 (H=3.7 m). Saline stratification at the mouth of the Amazon varied from a wedge form (slightly stratified) at the neap tide to and partially mixed (highly stratified) at the spring tide.

ADITIONAL INDEX WORDS: *Salinity, Amazon Estuary, Northern Channel*

INTRODUCTION

This study is part of the Sea Level Hydrodynamic Modeling and Monitoring of Amazon River's North Bar (BARRANORTE) project. The study area is located in the Northern Channel of the Amazon Estuary between the parallels 0°50'N and 1°50'N and meridians 48°50'W and 50°W, covering approximately 10,440 km^2. Data collection took place in 2006 and 2007. The objective of the study was to analyze the intrusion of saltwater into the Northern Channel in the context of physical forces, such as river discharge, winds and tides.

In the outer estuary of the Amazon, the principal dynamics are the semidiurnal macro-tide, constant trade winds, and the river's collosal discharge of freshwater (BEZERRA, et al., 2009). In addition to the expansion of our knowledge of hydrological systems, monitoring of the saltwater wedge helps in the mapping of large deposits of sediments, and contributes to the improvement of navigational and safety aids and environmental monitoring. From this perspective, we shall describe the general circulation features of the outer Amazon Estuary.

STUDY AREA

The Amazon River flows into the Atlantic Ocean through two main channels, to the north and south, which discharge onto the Amazonian Continental Platform. This platform extends 325 km into the Atlantic at the mouth of the river, but narrows to 210 km at the North Cape, and 125 km further north at Cape Orange (SILVA, 2006). The shelf is mostly around 15 m in depth, although a sandbar extends longitudinally through the estuary, about 100 km north, with minimum depths of around 9.5 m (GEYER, et al., 1996). A saltwater front is normally found close to the sea bed at this bar's mouth. This front is well defined, with freshwater from the continent at the surface and elevated salt levels at the bottom, originating from the sea (GEYER, et al., 1996).

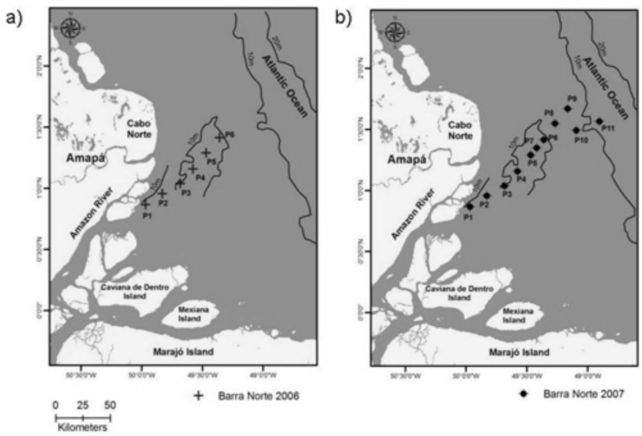

Figure 1. Location of the sampling stations (a) North Bar (June, 2006) and (b) North Bar (July, 2007).

The discharge of the Amazon River is equivalent to 18% of the freshwater released in the World's oceans. In addition, the river discharges about 11-13 x 10^8 tonnes of sediments per year, which are deposited on the northeastern portion of the inner shelf (PATCHINEELAM, 2004).

The liquid discharge of the Amazon is greatest in May-June and lowest in October-November. The discharge of sediments tends to precede peak water levels by two or three months, peaking in February-March. Some 85% to 95% of the suspended sedimentary material discharged by the Amazon is constituted of silt and clay, with a concentration varying between 0.02 and 1 g/L (KINEKE and STERNBERG, 1995). VINZÓN (1997), observed an area with a high concentration of sediments close to the bottom in the internal shelf at the mouth of the Amazon.

The influence of the tides on the Amazonian Continental Shelf is also important here. As the shelf varies considerably in width (125-325 km), it may have a significant effect on the semidiurnal components of the tide. BEARDSLEY, et al. (1995), indicates that the first three semidiurnal components (M2, S2 and N2) are responsible for 85% of the variation in the level of the water. More recent studies by GALLO, et al. (2007), also indicate the importance of the astronomical component M2 in the area.

The tide current in the region is around 1 m/s, running perpendicular to the local isobaths (BEARDSLEY, et al., 1995). There is also a significant fortnightly (springs and neaps) and monthly variation in tide levels and velocity. Near the Amazon's mouth, the strongest currents occur during spring tides (2 m/s) and the slowest (0.8 m/s) during the neaps (GEYER and KINEKE, 1995). In more recent studies, BEZERRA, et al. (2009), recorded neap tide velocities of over 1.5 m/s.

The local trade winds are most intense between January and April, when they blow predominantly from the northeast, and milder between June and October when they mainly blow to the west/northwest. This seasonal variation is determined by shifts in the position of the Intertropical Convergence Zone during the course of the year. On average, the trade winds direct superficial transport towards the Northern Hemisphere. As a consequence, parallel components of the coastal dynamics also direct subdiurnal currents to the northwest during the entire year in the inner portion of the continental shelf (FONTES, 2000).

According to PALMA (1979), the climate of the Amazonian Shelf varies from humid to super-humid with an annual mean precipitation of over 2,000 mm.

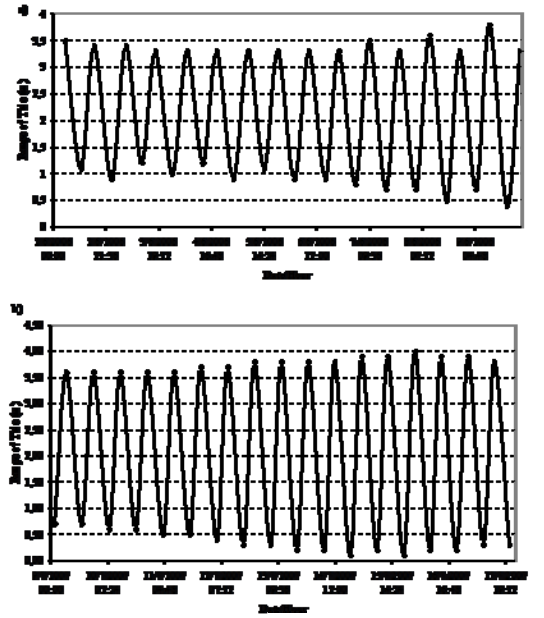

Figure 2. Tide prediction on the North Bar of the Amazon Estuary, at Ponta do Céu (Amapá). (a) June, 2006. Source: Brazilian Navy Hydrography and Navigation Office (DHN, 2006); (b) July, 2007. Source: DHN, 2007.

The outer Amazon Estuary is characterized by a highly dynamic environment, which is affected by both permanent (river-ocean interface) and seasonal (dry *vs.* rainy season) factors. Some of these factors are analyzed here for the period of peak discharge (in 2006) and immediately afterwards (in 2007). The data were collected on the Hydro-Oceanographic ship NHi Sírius, of the Brazilian Navy's Hydrography and Navigation Office.

METHODS

Data were collected during two campaigns, one in June, 2006 and the other in July, 2007, at 6 (six) and 11 (eleven) stations, respectively (Figure 1). Hourly profiles were collected over a 12-hour period at each anchorage. In the present study, only profiles which presented saltwater are analyzed. These were collected at station 6 in 2006, and stations 8-11 in 2007, and were analyzed for each phase of the tide (flood, high, ebb and low). The profiles were made using an SBE 19 model CTD (Sea-Bird Electronics, Inc.).

The tide data were obtained from the Brazilian Navy's Ponta do Céu station (Figure 2). This information was combined with readings from the ship's ecobathymeter of the ship to determine sampling times.

The sampling stations were georeferenced using a DGPS-type (Differential Global Positioning System) system (Table 1). These

Table 1: Location of the sampling stations included in the present study.

Station	Date	Latitude (N)	Longitude (W)
P6	08/06/2006	01°24'59.4"	49°21'26.4"
P8	15/07/2007	1º 32'56.7"	49°15'58.0"
P9	15-6/07/2007	1º40'16.7"	49º09'44.8"
P10	16/07/2007	1º29'32.8"	49º05'25.8"
P11	17/07/2007	01º33'58.3"	48º54'4.1"

stations were located in the same area as those of the AMASSEDS Project (A Multidisciplinary Amazon Shelf SEDiment Study), with the objective of comparing data.

The wind data were from the Quikscat satellite, obtained from the JPL Physical Oceanography Distributed Active Archive Center - PODAAC (PODAAC, 2008). Daily data for the months of April, May and June, 2006 and April, May, June and July, 2007 were acquired in order to obtain monthly averages of wind intensity and direction in the area of study.

The discharge data were obtained from the database of the Brazilian Water Agency (ANA, 2007), through the on-line Hidroweb application for the years 2006 and 2007. In 2006, the hydrological regime of the Amazon Estuary could be estimated from the sum of the discharge of the Amazon at Óbidos with the contributions of the Xingu (at Altamira) and Tapajós (at Acará do Tapajós) rivers. In 2007, this estimate could be made with the calculation proposed by GABIOUX (2002), in which the discharge into the estuary is estimated from the sum of that of the Amazon at Óbidos and the outflow of the Tapajós and Xingu rivers, the main tributaries downstream from Óbidos.

RESULTS

The vertical saltwater profile in each tide phase recorded at each station is shown in Figure 3. The satellite image of June 2, 2006 shows the shape of the superficial plume of the Amazon during the campaign (Figure 4).

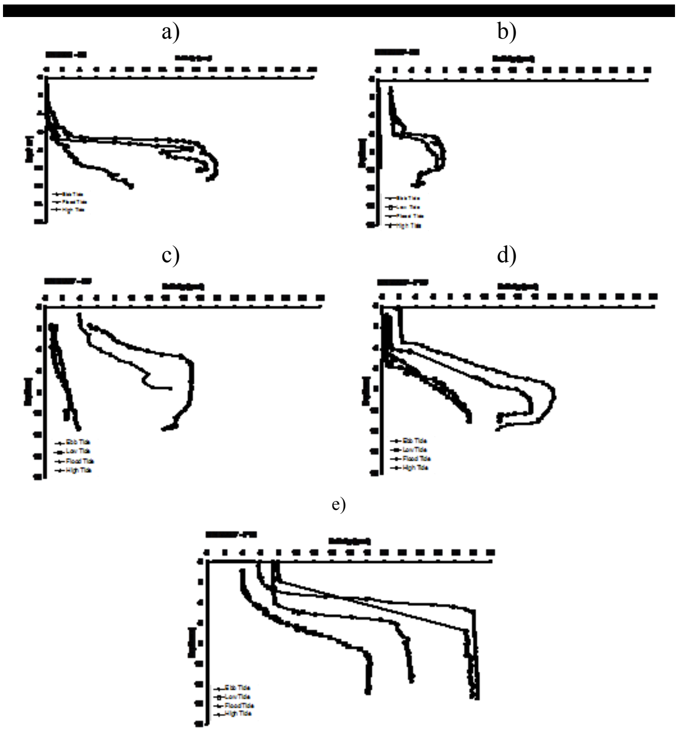

Figure 3. Vertical saltwater profiles. (a) North Bar 2006, station 6, 06/08/2006, (b) North Bar 2007, station 8, 07/15/2007, (c) North Bar 2007, station 9, 07/15-16/2007, (d) North Bar 2007, station 10, 07/16/2007, (e) North Bar 2007, station 11, 07/17/2007.

The saltwater profiles were used to estimate the position of the saltwater front. In June, 2006 the front was located 106 km from the coast (station 6). In July 2007, it had shifted to a distance of 121 km (station 8).

In April 2006, the average wind velocity varied between ~8 m/s and ~11 m/s under the influence of the northeast winds, between 45 and 25 degrees azimut (Az). In May means declined to between ~7 m/s and ~10 m/s, with the direction varying between 65 Az and 70 Az and 45 Az in the North. In June the intensity average varied between ~13 m/s and 15 m/s, and the direction between ~80 Az and 50 Az. In April 2007, mean wind speeds varied between ~4.19 m/s and ~11 m/s, predominantly from the Northeast (45 Az and 40 Az). During May, wind intensity decreased to between ~3.5 m/s and ~5 m/s, Northeast (~50Az). In June, mean intensity varied between ~8 m/s and ~14 m/s, and the direction between ~60 Az and 70 Az. In July, wind intensity of the wind was generally lower (9.1 m/s) than in the previous month, with a predominant direction of ~80 Az.

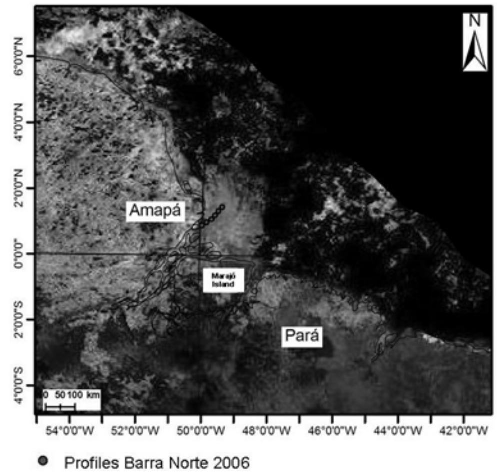

Figure 4. AQUA (MODIS sensor) 1R4G3B satellite image showing the sediment plume in the mouth of the Amazon during the 2006 campaign (image dated June 2, 2006).

The hydrological regime of the Amazon River estimated at Óbidos reached a maximum of 278,900 m^3/s at the end of May and a minimum of 87,574.00 m^3/s at the beginning of November, 2006. At the Estuary these values were 316,612 m^3/s in mid May and 95,953 m^3/s in early November, respectively. In 2007, maximum discharge at Óbidos was 237,813 m^3/s in mid June, falling to a minimum of 93,268 m^3/s. The maximum discharge at the Estuary was estimated at approximately 265,078 m^3/s.

ANALYSIS

During the 2006 campaign, saltwater was recorded at only one of the six stations (station 6). Salt levels were low or null at depths of up to ~6 m, but were were much higher below this depth, especially at the beginning of the ebb tide, with values reaching ~20 psu (practical salinity unit) (Figure 3a). The lowest value was 0 psu in all profiles.

In 2007, saltwater was recorded at stations 8, 9, 10 and 11. Their characteristics are analyzed below.

Station 8: Low (null) levels of saltwater during the ebb and low tides, increasing towards 8 psu in the flood tide. At high tide, the highest level of saltwater (~7.9 psu) was recorded close to the bottom (below ~9.5 m), with a slight inversion thereafter. The lowest value (0 psu) was recorded on the surface, in the low and ebb tide (Figure 3b);

Station 9: Similar to station 8, with low saltwater levels during the ebb and low tide (maximum of ~4 psu at the bottom). The saltwater wedge was more evident in the flood and especially the high tide profiles, with an accentuated gradient at a depth of between 4 and 5 m. The highest saltwater level was ~17.2 psu close to the bottom and the lowest was ~0.8 psu on the surface (Figure 3c);

Station 10: The saltwater wedge was more evident here, where lower salt levels extended down to a depth of only ~3.5 m. In the ebb and low tide profiles, saltwater levels varied from ~0.2 psu at the surface to ~10.2 psu at the bottom. The gradient was most accentuated between 4 and 6 m during the flood and high tide. The highest value of ~20 psu was recorded during the flood tide. There is also a clear inversion at depths below 9 m in the flood and ebb tides (Figure 3d).

Station 11: Brackish water at the surface, with a saltwater level of ~4 psu during low tide. The highest saltwater level was recorded during the flood tide, with 30 psu between 4 m and the bottom (13 m). The saltwater gradient is very sharp at the 4 m level (Figure 3e).

DISCUSSION

During the 2006 campaign, the saline wedge was found approximately 106 km from the mouth of the Northern Channel. BEZERRA, et al., (2009) analyzed the conductivity data of this location, from water collected at the surface, middle and bottom, which confirm the results of the CTD presented here. In June, the discharge at Óbidos was 274,600 m^3/s and the estimate of the total discharge in the estuary was of approximately 301,562 m^3/s.

During the 2007 campaign, the saline wedge was found at station 8, approximately 121 km from the mouth of the Northern Channel. However, the discharge of the Amazon at Óbidos was of approximately 220,300 m^3/s on the day the data were collected, and the estimated discharge at the mouth of the river (GABIOUX, 2002), was of approximately 246,300 m^3/s.

Comparisons with the data from the AMASSEDS Project are also relevant here. This Project conducted four campaigns between August, 1989 and November, 1991 (KINEKE and STERNBERG, 1995). Vertical saltwater profiles were collected during the flooding period of the hydrological regime of the river, at points RMo2405 (03/10/1990), RMi2444 (03/20/1990), RMo2445 (03/21/1990). Maximum discharge was recorded at points RMo3405 (06/02/1990) and RMo3455 (06/12/1990) and the minimum at point RMc4413 (11/16/1991).

We may estimate the position of the saltwater front based on the profiles of March 20 and 21, 1990, November 16, 1991 in comparison with those of the present study (Figure 5). While the profiles from point RMo2405 (03/10/1990) and 2007 were taken during the spring tide, all others were collected in the neap tide. In addition, only point RMc4413 (November, 1991) was taken during the period of minimum discharge of the Amazon.

As mentioned previously, several factors such as winds, river discharge and tides, influence the position of the saltwater front on the Amazonian Continental Platform. GEYER, et al. (1996) showed that the intensity and direction of the local winds may modify the structure of the sediment plume of the Amazon. These data confirm the results of NITTROUER, et al. (1995), which show the variation in the direction and intensity of the trade winds at the mouth of the Amazon.

In this study, by analyzing the intensity and direction of the wind, we may note that in 2006, winds were more intense (about 8 m/s stronger, on average) in the study area. We may thus suggest that the position of the saltwater bank have shifted due not only to changes in discharge levels, but also the influence of local winds. The reduced intensity of the northeasterlies in 2007, may have contributed to the extension of the plume an additional 14 km from the coast in comparison with 2006.

Another contributing factor may be the Northern Brazilian Current, which according to JOHNS, et al. (1990), becomes weaker in April and May, with values of 10 Sverdrup (Sv), and only strengthens from August/September, presenting values of 30 Sv. A possible difference in the intensity of the Northern Brazilian Current may thus also have favored the extension of the plume into the sea.

Tide records made by BEARDSLEY, et al. (1995) in the mouth of the Northern Channel indicated that the M2 component reaches values of around 1.5 m in this area. In the present study, a tidal range of 2.4 m was recorded for the neap tide (2006) and 3.7 m for the spring tide (2007). In the AMASSEDS Project, the saltwater front was located at 80 km from the mouth of the Northern Channel under minimum discharge conditions (November).

While the campaigns of 2006 and 2007 were carried out in the same hydrological period of maximum river discharge, the saltwater wedge shifted position by some 14 km. We suspected this could be explained by differences in discharge levels, although this was contradicted by the fact that the discharge was considerably lower (by some 54300 m^3/s, or 25%) in 2007. Given this, the considerable difference in tide levels (neap versus spring) may be the primary factor determining the shift in the saltwater front.

CONCLUSION

The Amazonian Continental Platform at the mouth of the Amazon River is characterized by a major freshwater-saltwater interface. The attributes and location of this phenomenon are influenced by both dirunal (tide) and seasonal (river discharge) components, and the analysis of both factors is equally important.

The local tidal range reaches 5 m, and may have a clear influence in the saltwater front. Saline stratification at the mouth of the Amazon varied from a wedge form (slightly stratified) at the neap tide to and partially mixed (highly stratified) at the spring tide.

Differences recorded between years in the location of the saltwater front appeared to be related primarily to tidal conditions rather than river discharge.

Surface wind data from the QuikScat scatterometer may support the study of the dynamics of the Amazon plume.

Physical forces such as tides, river discharge and winds in the outer estuary of the Amazon appear to be the primary factors determining the hydrological dynamics of the area, and obviously require a more systemic analysis, integrating other variables such as the local topography.

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