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Estuarine processes in macro-tides of Amazon estuaries: A Study of Hydrodynamics and Hydrometeorology in the Marajó Bay (Pará-Brazil)

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ABSTRACT

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The work carried out a hydrodynamic and hydrologic characterization in the estuary of the Para River (Marajó Bay), near the Colares and Guarás Islands (Pará, Brazil). The goal is to verify the behavior of the semi-diurnal macro-tide in large Amazon estuaries with an emphasis on hydrodynamic and hydrological characterization of the Pará River estuary. The work proposed as targets; to investigate the hydrodynamics as to stream and water level, and the physicochemical variations of the water body. The studies were conducted in quadrature and consisted of measurements of streams, salinity, temperature and tidal range. The main results showed that the Pará River estuary, as to the hydrological characteristics of the system, showed no significant variations in salinity throughout the water column in most profiles during the surveys. However, in Colares, there was an increase in the salinity over time, ranging from 3 to 5. On the Island of Guarás, the salinity was around 4 in the entire water column. The temperature in both, Colares and Guarás, did not vary, it was always 29ºC. These results show that, even during the drought period, with low flow, the effect of river water is one of the main forces of circulation, and even more important than mixing processes generated by the tide. As to the hydrodynamic characteristics of the system, it was found that stream direction during sampling varied widely, and was usually followed by low speeds. Overall, the estuary shows circulation of a very mixed kind, being mainly controlled by river discharge and secondarily by the oscillations of the tide. It is important to continue studies in this region, because the estuarine processes in macro-tides of Amazon estuaries are complex and do not have characteristics in common with other macro-tides estuaries due to the great flows of rivers in the Amazon region.

ADDITIONAL INDEX WORDS: *Amazon estuary. Pará River estuary. Macro-tidal estuary. Well-mixed estuary. Hydrodynamics. Hydrology*

INTRODUCTION

This study is part of the Field and Satellite Oceanographic Measurement project (code: IG0100921C) of the Integrated Support Program for Teaching, Research and Extension (PROINT 2008 - 2009) of the College of Oceanography, Federal University of Pará (Universidade Federal do Pará - UFPA) and the Hydrodynamic and Hydrometeorology Study of the Marajó Basin (Pará) (Ref. Proc.: 483113 / 2009 -3) financed by the CNPq and carried out by the Institute of Sea Sciences (Instituto de Ciências do Mar -LABOMAR) of the Federal University of Ceará (Universidade Federal do Ceará - UFC).

The research area for this study is located in the Brazilian Amazon Coastal Zone (ZCAB), between the parallels 4º S and 5ºN and the meridians 43º W and 51º W, between Cabo Orangen (Amapá) and Ponta de Tubarão (Maranhão), measuring nearly 2,250 km of estuaries and coastal islands (Souza Filho *et al*., 2009. This region is inserted in the context of wet, tropical regions that are characterized by heavy and constant rainfall, high temperatures with low thermal variation and elevated cloudiness (Nittrouer et al. 1995).

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This unique ecosystem with gigantic dimensions forms a large estuary at its mouth. Since this is defined by an analysis of the oceanographic properties in the area characterized by a mixture of fresh and salt waters, in the case of the Amazon River, it could called an "estuarine system", whether considering the Amazon and Pará Rivers as two distinct bodies of water, or as components of the same indivisible body of water (Diegues, 1973).

According to Corrêa (2006), the circulation process that occurs between the Marajó Basin estuary and the open sea is the mixture of freshwaters from the draining of the Pará and Tocantins Rivers, the Guajará Basin complex, with the salt water from the ocean, in a semi-restricted environment.

The Pará River, also known as the right/south branch of the Amazon River, separates the south and east of Marajó Island from the continent (state of Pará), joining the Amazon River at the Breves Strait (Souza, 2006).

According to Gregório (2007), the Pará River, which also comprises Guajará Bay, and which borders the city of Belém, is an environment with strong peculiarities with hydrodynamic characteristics strongly influenced by river and sea forces.

The study area is inserted in the Pará coastal zone, which has about 1200 km of coastline and is divided into 3 sectors: Sector 1, or the Salgado Paraense Atlantic Coast; Sector 2, the Continental Estuary and; Sector 3, the Insular Estuary (GERCO, 1996). The study area is located in the Salgado Paraense Atlantic Coast (sector 1).

The Pará River is very important for local and regional navigation since it provides access to the main ports in the northeast of Pará, in Belém, the state capital. The Pará River is an efficient connection of the region with the rest of the world due to its privileged geographic position as well as the large extension of mooring berths, with a 14-meter depth, and with easy sea and river access.

Another important reason for studying the region is because it is an estuary, a transition ecosystem between the ocean and the continent; the complexity and vulnerability of human influence are common characteristics for all estuaries.

However, even with such importance for the environment and navigation, the Pará River region is still lacking in studies, especially with regard to the physical aspects, thus justifying this study.

This paper conducted a hydrodynamic and hydrological characterization of the Pará River estuary (Marajó Basin), near the Colares and Guarás Islands (Pará, Brazil) (Figure 01). The objective is to verify semi-diurnal macro-tidal behavior in large Amazon estuaries with an emphasis on the hydrodynamic and hydrological characterization of the low Pará River estuary during the dry season.

This study proposed the following goals: (01) Investigate the region's hydrodynamics in a study specifically related to currentometry and water levels; and (02) Investigate the physical-chemical variations of water (salinity, conductivity and temperature).

METHODS

The study area is located in the low Pará River estuary, in the Marajó Bay, near Colares Island and Guarás Island. The choice of these areas is related to their geographical location. Colares is more inside the estuary and Guarás is closer to the mouth. The objective was to longitudinally observe the variations in the hydrodynamic hydrographic processes. (Figure 1)

On Colares Island, the field work was conducted on December 7-8, 2008, during the dry season on Pará River, at neap tide. The studies began at 9:00 pm on the 7th and finished at 8:00 pm on the 8th, totaling 24 hours of monitoring the physical processes related to tide, such as the high tide, low tide, flood tide and ebb tide.

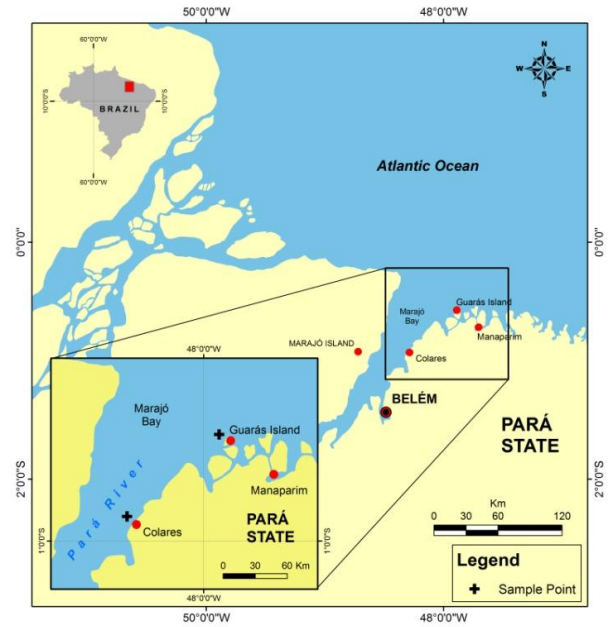

Figure 1. Study area with the location of sampled stations, near Colares and Guarás Island. (Marajó Basin, Pará River – Pará, Brazil).

On Guarás Island, field work was conducted December 9-10, 2008, during the dry season on Pará River, with normal tide. The studies began at 7:00 pm on the 9th and finished at 9:00 am on the 10th totaling 14 hours of sampling.

It is important to mention that the results from Guarás Island could have had a longer series, however in open areas in the Amazon region, the infrastructure with the vessel is a problem, especially during the second semester of strong winds, which generate waves of nearly two meters in which many vessels cannot withstand the adverse conditions for navigation, forcing the motor, or with the entry of water, etc., putting the crew at risk and risking the loss of instruments.

The activities plan raised the profile of currents using Acoustic Doppler Current Profiler – ADCP, model RDI Rio Grande 600; and the water's physical-chemical profile using a Conductivity-Temperature-and-Depth – CTD probe, model SBE 37 - SM MicroCAT. Tidal graph data were obtained from the Brazilian Hydrography and Navigation Bureau`s (Diretoria de Hidrografia Nacional do Brasil – DHN) tidal table.

Twenty-four launches were made from the CTD to obtain a continuous vertical profile along the water column to observe the variations throughout a tidal cycle. The CTD was programmed to make measurements every 5 seconds, saving the data on computer after each launch.

The ADCP used was affixed to the side of the vessel and at approximately 0.7 meters in depth with its compass configured for the Magnetic North. Files were saved every hour during the work period, always aimed at being simultaneous with each CTD launch.

Flow data were measured by the ADCP for the point sampled and not for the estuary section.

A Global Positioning System – GPS was also used, Garmin, model 76CSx, for marking the collection station.

Instrument data were plotted on spreadsheets for later treatment in proper software and for elaborating graphs and maps.

RESULTS

Hydrological Characteristics of the Estuary System – Salinity and Temperature

There were no significant variations in salinity along the water column in most of the profiles during collections; however, in Colares there was an increase in salinity over time, ranging from 3 to 5.

In Colares, at profile Nº1 to Nº6 and from profile Nº9 to Nº12, salinity increasingly varies with a depth of at most 2. At flood tide, salinity at the upper layer in profiles Nº7 and Nº8, it is slightly higher than the bottom salinity, but the difference is very small, at most 0.14.

On Guarás Island, salinity was around 4 throughout the entire water column. The vertical profiles for salinity on Guarás Island have the same behavior as Colares where salinity varies increasingly with depth at a maximum of 1.5. The hydrographic results for Guarás Island are shown in figure 2.

In the Colares profiles, salinity is higher during the first hours of ebb tide and salinity is lowest at the end of ebb tide. This is peculiar behavior that could probably be attributed to the removal of salts in areas flooded by the tide. Colares salinity and temperature profiles are shown in figure 3.

In general, salinity in the Marajó Bay study area for the dry period and at neap tide in 24 hours saw a minimum of 1.7 and a maximum of 5.6.

The temperature in Colares as well as Guarás did not vary, and was stable at 29ºC.

These results show that even in the dry season with low flow, the river discharge effect is one of the main forces of circulation, being more important than the mixture processes generated by the tide, because the variation in salinity is low.

Hydrodynamic Characteristics of the Estuary System – Currents

On Colares Island, maximum tidal speed occurs at ebb tide and it is 1.019 ms^{-1} and the flow measured by ADCP at this point for that time was 13.711 m^3s^{-1}. Minimum speed was recorded at the beginning of flood tide near the turn in tide, with 0.023 ms^{-1} and the flow measured by ADCP at this point at this instant was 1.255 m^3s^{-1}. Data on current evidenced an alternative and axial character in flood tide and ebb tide currents, at 243º to 267º and 34º to 43º, respectively. The current direction is the Magnetic North.

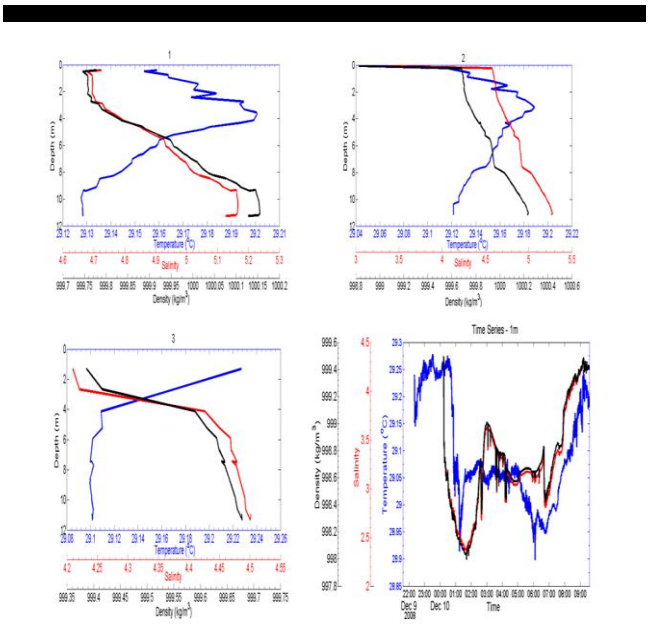

Figure 2. Vertical profile for salinity and temperature versus depth in Guarás Island and Temporal series for salinity and temperature at a depth of 1m on Guarás Island (Marajó Bay, Pará River).

The system of currents presented variations in direction and intensity mainly tied to tidal oscillations and channel morphology. The ADCP data revealed that the current direction varied greatly during sampling, indicating when it was ebbing and flooding. Part of the profiles for change in tidal direction presented the most diversified current throughout the water column and, generally, they were accompanied by low velocities (Figure 4A, 4B and 5A).

The flows obtained with ADCP for the point sampled on Colares Island showed that the ebb tide flows are superior to those observed in flood tides. At flood tide, the greatest flow is 78.65 m^3s^{-1} at 11:30 am, and at ebb tide, the greatest flow is 176.122 m^3s^{-1} at 07:29 am. The lowest flows are at ebb tide, 0.30 m^3s^{-1} at 01:24 am, and at flood tide, 1.35 m^3s^{-1} at 12:46 pm. (Figure 4C)

Colares results did not present a consistent association between greatest flow speeds and greatest flows to the estuary. A delay was observed in speed in relation to flow. Peaks of greatest flow were recorded that precisely correspond to the greatest current speeds.

On Guarás Island, in the 14 hours of oceanographic campaign, the greatest current speed was recorded at flood tide with 1.393 ms^{-1} at 00:14 am and the lowest current speed at ebb tide, with 0.129 ms^{-1} at 8:04 pm.(Figure 6A and 5B). Flow data obtained do not present any consistency, with some being very abrupt. (Figure 6B)

With regard to the classification based on the convergence / friction ratio, the Pará River is hyposynchronic, that is, tide height, diminishes into the estuary. On Guarás Island, maximum height is 4.4 m and on Colares, 3.2 m. Baltazar, Bezerra Menezes and Rollnic (2011) conducted a study on Colares on December 17-18, 2009 during syzygy and observed that average speed in the water column obtained maximum values of 1.15 ms^{-1} and minimum values of 0.04 ms^{-1}. These authors compared the tidal tables for Mosqueiro Island (DHN) and field data in the Colares Island region in April 2008 and verified that the difference between curves is 47 minutes in advance and 0.36m in amplitude above for Colares. Salinity in the 24 hour period saw a minimum of 2.2 and a maximum of 5.6, Salinity is a little odd, with higher values and stratification in the water column during the first hours of ebb tide. The estuary systems assumes well-mixed, type 1 characteristics.

In this study, at neap tide at the end of November 2008, the salinity in Colares was a maximum of 3. It also presented higher values for salinity at low tide, corroborating with the data from Baltazar, Bezerra Menezes and Rollnic (2011). This probably occurs due to the removal of salts in areas flooded by the tides.

On Guarás Island, salinity was around 4, higher because it is at the mouth of Pará River.

With regard to the current speed values in Colares, they are compatible with those found in Baltazar Bezerra Menezes and Rollnic, (2011), with maximum tidal speeds at ebb tide and at around 1.019 ms^{-1}.Bezerra, *et al*. (2011) conducted studies in front of Belém (Miramar Terminal) on October 25 and 26, 2007, at syzygy tide. The authors observed that salinity did not present expressive variations over the 24 hour measurement period, and the maximum salinity value was 1.6.

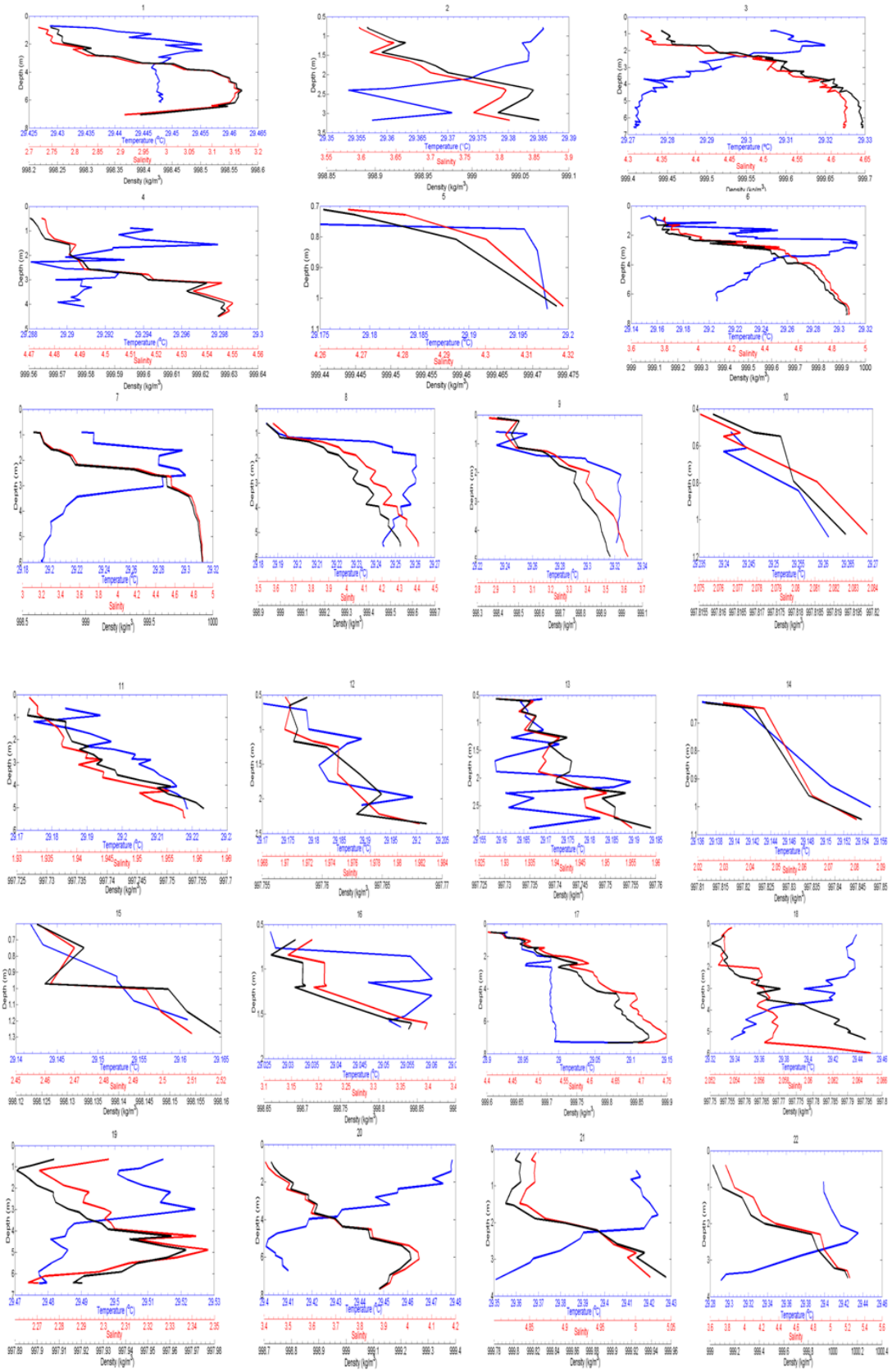

Figure 3. Vertical profiles Nº1 - Nº22 for salinity and temperature versus depth in Colares (Marajó Bay, Pará River). Salinity (red), temperature ºC (blue), density Kg/m^3 (black).

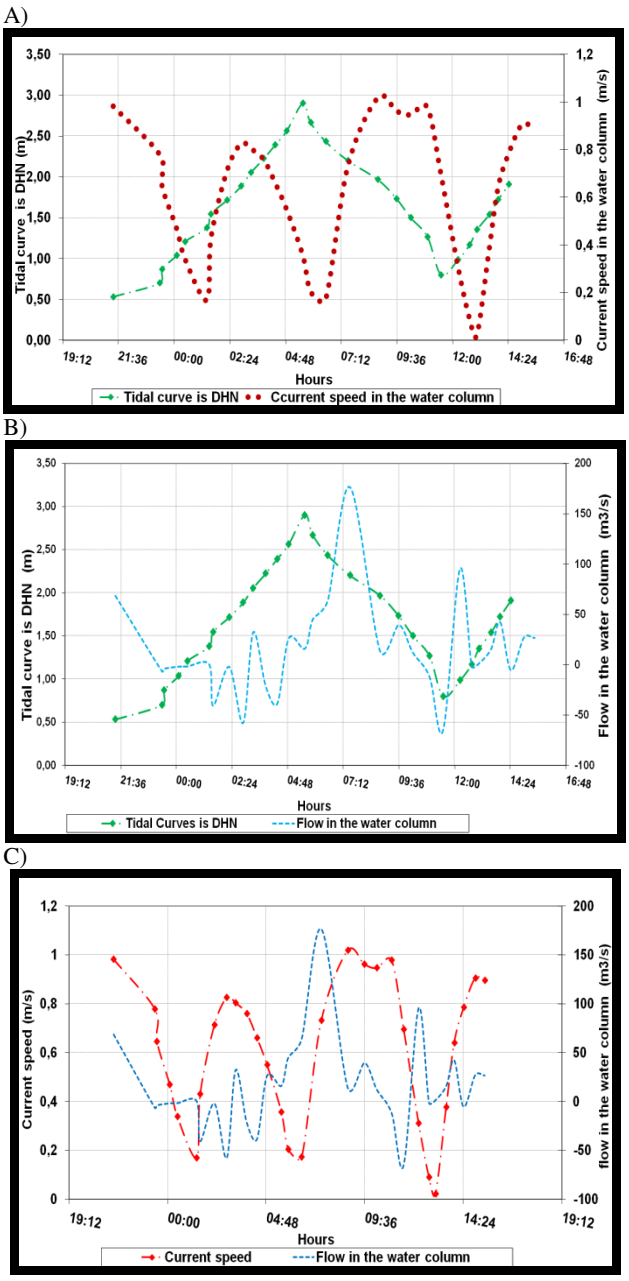

Figure 4. A)Relation between average current speed in the water column and the tidal status on Colares at neap tide (Marajó Bay, Pará River). The tidal curve is DHN for Mosqueiro, which is near Colares; B)Relation between the DHN tidal curves with flow in the water column measured by ADCP for the point sampled on Colares Island (Marajó Bay, Pará River) The tidal curve is DHN for Mosqueiro, which is near Colares; C) Relation between average current speed in the water column and the flow measured by ADCP for the point sampled on Colares at neap tide (Marajó Bay, Pará River).

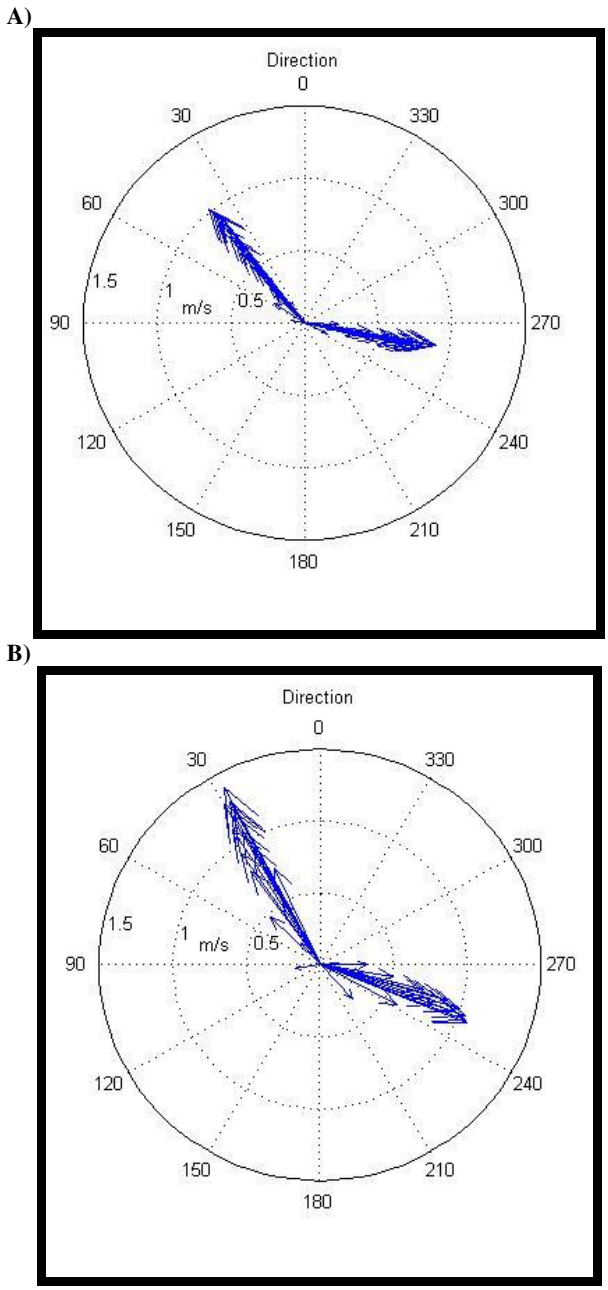

Figure 5 A)Current direction and speed vectors for Colares at neap tide (Marajó Bay, Pará River), B) Current direction and speed vectors for Guarás Island at normal tide (Marajó Bay, Pará River). * Compass configured for the Magnetic North.

That is, lower than that found by Baltazar, Bezerra Menezes and Rollnic (2011) in Colares and in this study, which was 2. In Belém, lower salinity is expected because it is the most inner portion of the Pará River for the three areas of comparison: Guarás, Colares and Belém.

Bezerra *et. al.* (2011) observed the tide asymmetrical, with approximately 5 hours to flood and 8 hours to flow, and the maximum speed is 1.4 ms^{-1} at the surface during ebb tide, and the maximum speed at the bottom is 0.97 ms^{-1} also at flood tide. The lowest current speed at the surface was 0.4636 ms^{-1} at the beginning of flooding and the lowest speed at the bottom was 0.163 ms^{-1} at high tide.

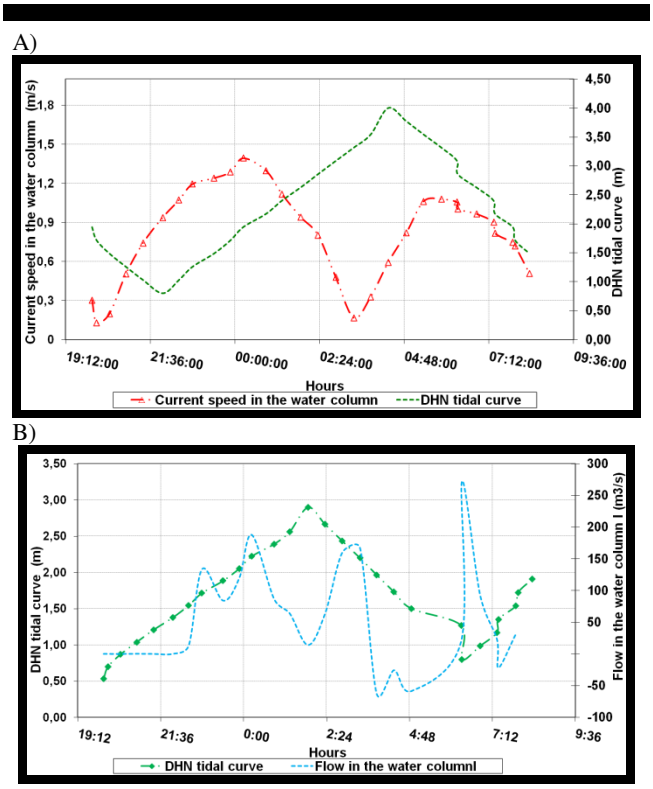

Figure 6. A) Relation between average current speed in the water column and the tidal status on Guarás Island at neap tide (Marajó Bay, Pará River). The tidal curve is DHN for Guarás; B) Relation between DHN tidal curve and total flow in the water column for Guarás Island (Marajó Bay, Pará River).

CONCLUSIONS

The results showed that the estuary system's hydrological characteristic did not present significant variations in salinity throughout the water column in most profiles during collection. However, on Colares there was an increase in salinity over time, ranging from 3 to 5.

On Guarás Island, salinity was around 4 throughout the water column. In general, salinity in the study area in the 24 hour period revealed a minimum of 1.7 and a maximum of 5.6. The temperature on Colares and Guarás did not vary, and was always at 29ºC. These results show that even in the dry season with low flow, the river discharge effect is one of the main forces of circulation, being more important than the mixture processes generated by the tide.

The Pará River estuary is characterized as a well-mixed estuary with a saline regime ranging between limnetic and mesohaline with tidal oscillation. The tide reached a maximum height greater than 4 meters, characterized as macro-tidal, and exercising a fundamental role in the estuary mix. Although the tide is an important environmental agent in the mixing process, the estuary is mainly controlled by the river discharge and secondarily by tidal oscillations.

The hydrodynamic characteristics of the estuary system, especially the currents, obtained with ADCP, showed that the current direction varied much during sampling, indicating when it was ebbing and flooding. Part of the profiles for change in tidal direction presented the most diversified current throughout the water column and, generally, they were accompanied by low velocities.

Current speeds presented a predominance of ebbing compared to the flooding tide, for Colares Island and for Guarás Island. Similar behavior was observed for flows, with ebb tide flows greater than those observed for flood tide.

This study contributed towards an understanding of physical oceanographic processes in Marajó Bay, PA, and it is important to give continuity to the studies in this region because the estuary processes in macro-tides in Amazon estuaries are complex and do not have characteristics in common with other macro-tidal estuaries due the great flow of Amazon Rivers.

ACKNOWLEDGEMENT

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