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Contributions to the Understanding of Physical Oceanographic Processes of the Marajó Bay - PA, North Brazil.

L. R. S. Baltazar†, M. O.B. Menezes‡ and M. Rollnic†

†Universidade Federal do Pará
Brasil
baltazar_lr@hotmail.com

‡ Universidade Federal do Ceará
Brasil
ozilea@gmail.com

†Universidade Federal do Pará
Brasil
rollnic@ufpa.br

ABSTRACT

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The island of Colares is located in the northeast of Pará and bathed by the Pará river estuary. This study intended to characterize the hydrodynamic and hydrological processes of the lower estuary of the Pará river during the dry period. The field research was conducted at December 17th and 18th , 2009, during the dry season, with spring tide of new moon, on board of a catamaran, a sounder Conductivity-Temperature-and-Depth (CTD), an Acoustic Doppler Current Profiler (ADCP) and a digital anemometer. Weather showed different conditions, which may be consequences of the El Niño event, the currents system of the estuary showed variations of intensity and direction related mainly to changes in tide and the channel morphology. The average speed in the water column obtained values maximum to 1.15 m/s and minimum of 0.04 m/s. The surface current speed was more intense than the bottom. The results of the wind showed many fluctuations, with hours of great gusts, reaching 13m/s, and other of calm, with speed very close to 0 m/s. The tide on the island Colares presented maximum amplitude of 3 m, 0.36 m higher amplitude compared to Mosqueiro island, and an advance of 47 minutes. The salinity in the estuary is strongly influenced by the tide, being some what peculiar, with higher values and stratification in the water column in the early hours of ebb. According to the stratification-circulation diagram of Hansen & Rattray (1966) the Pará River estuarine system assumes characteristics of type 1 (well-mixed) without vertical stratification.

ADDITIONAL INDEX WORDS: *Hydrodynamic, well-mixed estuary, Amazon estuary macro.*

INTRODUCTION

This study is part of the Integrated Program of Teaching Support, Research and Extension (PROINT 2008 - 2009), of Oceanography College.

The study area is situated on Amazonic Coastal Zone (ACZ), placed within the context of the humid tropics, between 4º N and 4ºS. Specifically in Marajó bay (Pará river), coastal zone of the Pará state, near Colares island (figure 1).

The Pará river is very important to navigation, once it gives access to majors ports of Pará's northeast. Another importance to study this region that is an estuary, a transitional ecosystem between the ocean and the continent; the complexity e vulnerability to the influence of men are common characteristics to all estuaries. In natural conditions, the estuaries are biologically more productive than the river and ocean adjacent, by high concentration of nutrients that stimulate the primary production (Miranda et al., 2002). The Pará river receives water of the largest watershed in the world, the Amazon river basin, and also the Tocantins/Araguaia basin and Atlantic North-Northeast basin.

However, even with such importance, the region of Pará river has still few studies, lacking much for his characterization, especially regarding to physical aspects, justifying the present study, that shows with general goal to help in knowledge and characterization of hydrological and hydrodynamical processes of lower estuary of the Pará river, in Marajó bay's region, in the end of dry period (December).

Towards this, it was intended to investigate the hydrodynamic and the temporal variability of hydrological properties and circulation of lower estuary of the Pará river, near Colares region, in end of the dry period in spring tide; to identify and to relate with the pattern of currents and the presence of salinity; to classify the estuarine system trough the stratification-circulation diagram of Hansen & Rattray (1966) and; to analyze the tide current velocity components from the axis of coordinates to a tide cycle in the area of study.

METHODS

The Colares island is limited for geographic coordinates represented by the parallels 00°09'S and 01°01'S and by the meridians 48°09'W and 48°19'W Gr (Tuma, 1997) and the sample point is in 00º55'30,9''S, 48º17'58,62''W (figure 1).

The field research was conducted at December 17th and 18th , 2009, during the dry period of Pará river, with spring tide of new moon. The studies began at 15:00 hs of 17th and were completed at 15:00 hs of 18th, making a total of 24 hours of monitoring physicals process related with the tide. The research was conducted with a sounder Conductivity-Temperature-and-Depth (CTD), an Acoustic Doppler Current Profiler (ADCP) and a digital anemometer. The CTD was used for data acquisitions of conductivity and depth. The equipment, coupled to a cage, was released every hour with a total of 24 releases, so that the variations were observed over a tidal cycle.

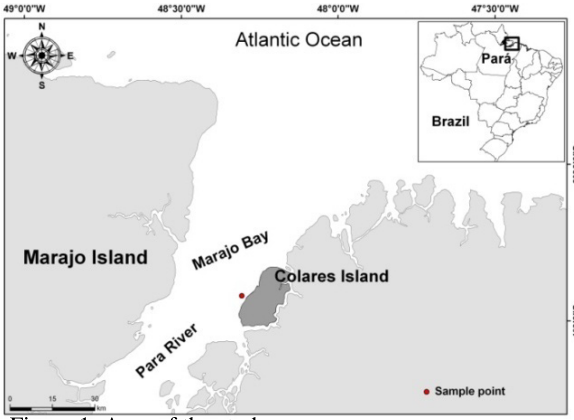

Figure 1: Area of the study.

The ADCP used to acquire current data (intensity and direction) was fixed on the side of the ship about 0,7 m of depth. The files were saved every hour during the study period, like the CTD's release and the wind data measurement. For this, was used a digital anemometer with collection in upper of the ship (about 6 m in height in relation to the water surface) and online data from Institute National of Meteorology (INMET) of precipitation, accumulated precipitation and insolation. The quantitative classification will be made with stratification-circulation diagram of Hansen and Rattray (1966).

Hansen and Rattray (1966 apud Miranda et. al., 2002) implemented a classification method based on tide velocities associated with the fresh water inflow of residual circulation vertical system, whose it's defined in four basic categories: Type 1 (type 1a - weakly stratified and type 1b – where the stratification of salinity is moderate); types 2a and 2b (represent partially mixed estuary); types 3a and 3b (they are the estuaries type Fiordes) and; type 4 (typical of highly stratified systems such as estuaries of saline).

RESULTS

Hydroclimatic Contextualization

According with the graphics data of INMET, the climate in region of study in December of 2009 was drier than the previous year (figure 2), with zero of monthly accumulated precipitation of Soure, located on the shore of Marajó bay opposite the study area. There was also high amount of daily hours with insolation in the research days, December 17th, was one of it that showed highest amount of hours with incidence of sunlight.

The accumulated precipitation in the research days has indices equal to zero, it was verified in field. The forecasting rain to North region is normal to below normal climatological. While the temperature should be presented above normal climatological (Melo, 2009).

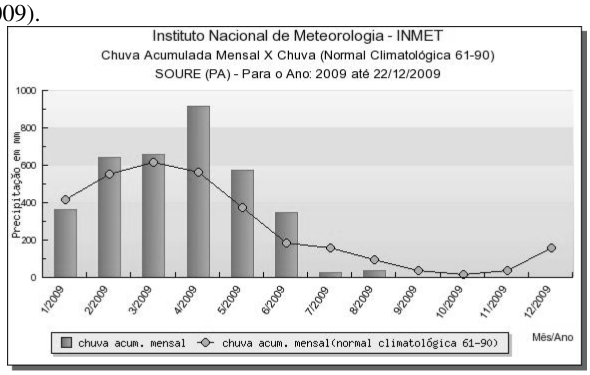

Figure 2: Accumulated precipitation in Soure show the climatology to the region of the study area in 2009. Source: INMET.

Circulation and Mixture Process

Wind regime

The average wind during the sampling, showed many fluctuations, with hours of large bursts, reaching 13 m/s at 17:00 hs of 17/12/09, and others of lull with speed to close 0 m/s at 4:00-5:00 hs of 18/12/09 (figure 3).

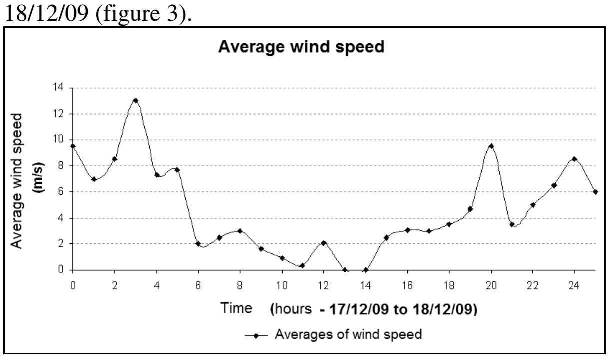

Figure 3: Average wind speed during sampling period, from 15:00 hs of 17/12/09 to 15:00 hs of 18/12/2009.

As for the variation of wind direction, it had a tendency Northeast (NE) and East (E) (figure 4). However, it showed also bursts on North (N) and Southeast (SE) directions.

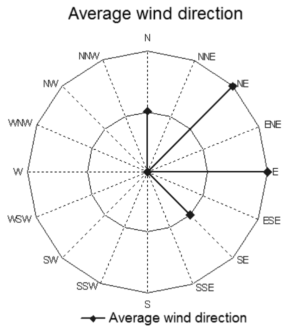

Figure 4: Average Wind direction graphic during the sampling, December 17th and 18th, 2009.

Tides

According to Baltazar *et. al.* (2010) the comparison between the tide data (variations in height of the tide and times of the waves) of the preview to Mosqueiro island and the field data on region of Colares island of April of 2008 revealed an average difference 47 minutes of advance the parameters of wave on Colares island and 0,36 m above of the variation in the height of the tide that arrived on Mosqueiro island.

Based on discrepancies in the data obtained and in the preview of tide to Mosqueiro island in April, 2009, Baltazar *et. al.* (2010) estimated the tide to Colares island for same period, showing a maximum in the height of the tide of 3,86m and minimum of 0,56m (figure 5).

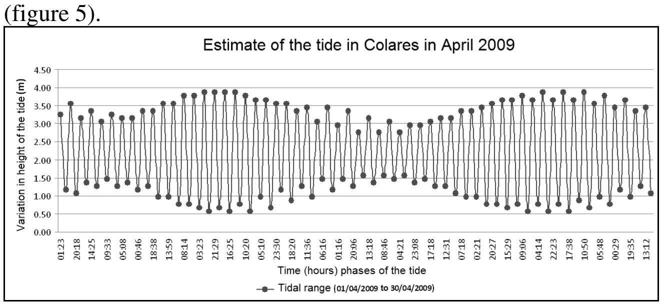

Figure 5: Estimate of the hour and variation in the height of the tide to study area in period from April 01th, 2009 to April 30th, 2009.

Assuming that the same error in the estimate of April, 2009, occurred in December, 2009, Baltazar *et. al.* (2010) made estimate to this month, and the variation in the height of the tide during the month showed maximum of 3,86 m and minimum of 0,46 m. In the study period (December 17th - 18th) the estimate of the Colares tide showed maximum in the tide height of 3,56 and minimum of 0,56 (figure 6).

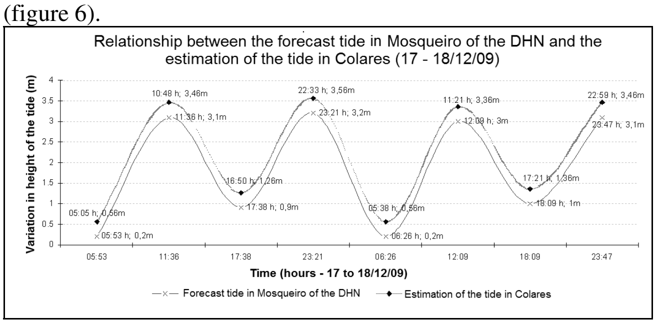

Figure 6: Estimate of the hour and height variation of the tide to study area during the period from December 17th to 18th, 2009.

Currents

With ADCP data verified that the current direction varied greatly during the sampling, indicating when it was ebb and flood, about 45º and 225 º respectively (figure 7).

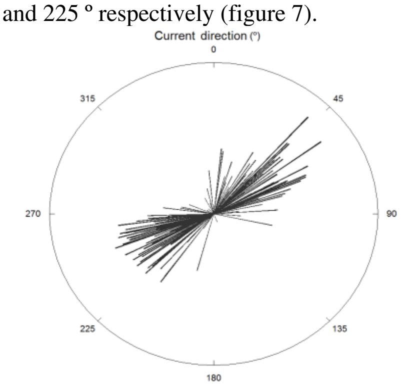

Figure 7: Current direction during the sampling.

When the current direction varied greatly in same profile, it showed the change of tide phase, especially if it was accompanied by low speed.

Was verified the period of tide phase of ebb and flood were 7 hs and 6 hs, respectively. The fate of the period of tide flood and ebb are different, it classifies the estuary like asymmetric, because, according with Miranda *et. al.* (2002), if the intervals of flood and ebb time are different, it follows the Principle of Conservation of Volume in the event of shorter duration, where the speed of movement will be more intense and, in consequence, the sediment transport will be greater, assuming an adequate supply of sediment in both events.

Most of the current velocity profile, in several hours during the sampling, showed a falling tendency along the water column (figure 8), with speed maximum of 1,7 m/s (ebb) and minimum of 0,3 m/s (flood) on surface and, on bottom, the maximum speed was 1,07 m/s (ebb) and minimum 0,3 m/s (flood). The average speed in water column had maximum values of 1,15 m/s and minimum of 0,04 m/s.

The current velocity varied greatly during sampling period, and it showed large magnitude, in times of ebb and flood, reaching an average surface maximum of 1,16 m/s. Besides presenting four "negative peaks" that is padding tide, moment where the speed is minimum and the current changes of direction, two of flood and two of ebb.

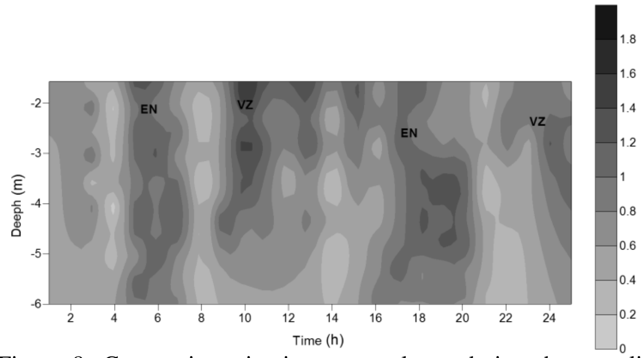

Figure 8: Current intensity in water column during the sampling period, beginning at 15:00 h of 17/12/09 and finishing at 15:00 h of 18/12/09. EN = Flood and VZ = Ebb.

The surface current velocity was, generally, more intense than the bottom. The frequency of surface current (figure 9 a) showed more uniformity, with more regularity in the direction, than the bottom currents (figure 9 b).

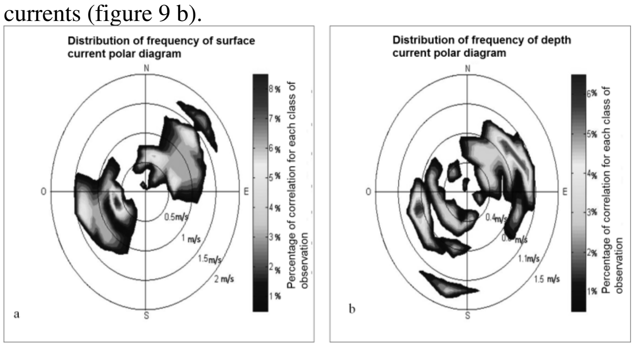

Figure 9: Polar diagram of distribution of frequencies of surfaces currentes (a) and bottom currents (b) during the sampling period, 17/12/09 to 18/12/09.

Hydrological Characteristics of the Estuarine System

Salinity and Temperature

There weren't significant variations in the salinity/ temperature in water column in several flood profiles (from 18:00 to 23:00 hs of 17/12/09; from 07:00 to 12:00 hs of 18/12/09). However, there was a increase of salinity over time during the flood, ranging from 2,1 to 4,7 in the flood at 18:00 to 23:00 hs of 17/12/09 (ex. in the figure 10); and from 2,4 to 4,2 in the flood at 07:00 to 12:00 hs of 18/12/09.

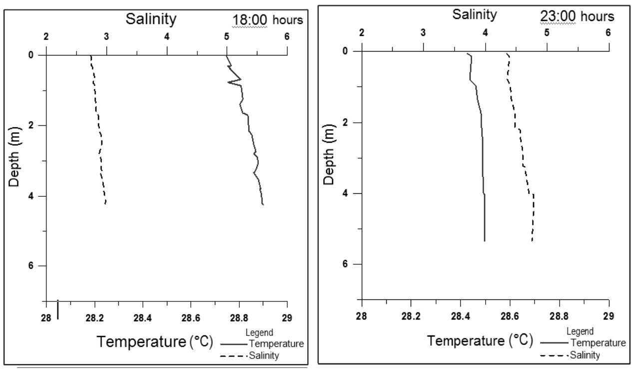

Figure 10: Graphics of salinity and temperature versus depth of flood at 18:00 hs and at 23:00 hs of 17/12/09.

The temperature in water column in ebb period also didn't show significant variations, exception the profiles at 15:00 hs (17/12), 01:00 hs (18/12), 13:00 hs (18/12) and 14:00 hs (18/12).

The opposite occurred in ebb profiles to salinity, whose was observed a largest variation, with maximums recorded each phase equivalent to: 3,7 (ebb at 15:00 - 17:00 hs of 17/12); 5,6 (ebb at 00:00 - 06:00 hs of 18/12) and; 4,4 (ebb at 13:00 - 15:00 hs of 18/12).

There was a stratification in ebb profiles at 00:00 hs - 01:00 hs of 18/12 and, 14:00 hs of 18/12. The salinity in the study area during 24 hours had a maximum of 5,6 and a minimum of 2,2, as can be seen in the graphics of figure 11 (at 00:00 hs and at 07:00 hs). This variation occurred during an interval of seven hours.

The temperature of the water in region of study didn't show larges variations along the vertical profile. However, there is variations along the time, with maximum of 28,9°C (at 17:00 hs of 17/12) and minimum of 28,1°C (at 01:00 hs of 18/12) in an interval of eight hours between the ebb profiles.

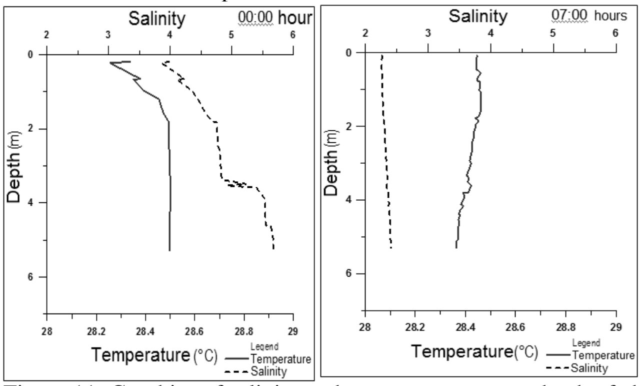

Figure 11: Graphics of salinity and temperature versus depth of ebb showing the maximums and minimums salinity during the sampling.

Classification of Estuary Using the Diagram of Stratification-Circulation of Hansen and Rattray (1966)

According with the classification obtained through the stratification-circulation diagram of Hansen and Rattray (1966), for this study, observed that the estuarine system assumes characteristics of type 1 (well mixed) without vertical stratification. In the different types of tidal stages, the estuary of Pará river behaves as type 1a, weakly stratified and type 1b, which the salinity stratification was moderate, but near bottom there didn't result an estuary flow above (figure 12).

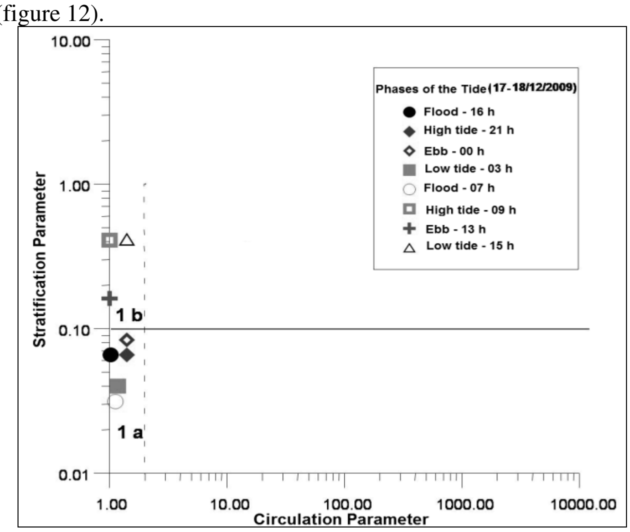

Figure 12: Diagram of classification of Stratification-Circulation of Hansen and Rattray (1966).

DISCUSSION

About the climate showed during the sampling, indices higher of insolation and indices very low of rain can be explained for fate of year 2009 was influenced by El Niño. The perspective is that the sea to warm up to two degrees above of normal, what represents an El Niño from moderate to strong. It exacerbates the naturals conditions in each micro region of South America; while the South is drowned by quantities of rain up to five times above of the average, in the North and Northeast of country, the situation is the opposite, with a drought as the years have not see, showing less than half the usual rainfall (EFEITOS..., 2009).

The samples of wind that recorded major speeds, above 4 m/s, were during the day. Occur more intense during the day cause for major air heating for insolation, because the main cause of these movements are the difference of temperature.

According Baltazar (2010), the tide at Colares island on April of 2009 showed generally, according with the estimates, larger amplitudes than Mosqueiro island and their wave characteristics arrived before, because the Colares island is further downstream of Para river than Mosqueiro island. And more, the relationship of the interaction between the wave tide propagating up estuary above and the morphology of estuary, can to classify the Pará river estuary according Nichols and Biggs (1985 apud Dyer, 1997) like hiposincrono, because the height of tide decreases along the estuary. In the first sampling profile (at 15:00 hs to 17/12), the current was ebbing, however the salinity showed higher than in the two first profiles of flood (at 18:00 and 20:00 hs of 17/12). This was also verified, and with more intensity, in the profiles of second ebb of the sampling (from 00:00 to 06:00 hs of 18/12), that showed salinity higher than the firsts profiles of next flood (from 07:00 to 10:00 hs of 18/12).

Regarding tide currents, the direction had a lot of variation, especially because the tide alternate between ebb and flood. Being the studied area a river that shows channels with orientation approximate Southwest-Northeast, therefore when the tide current direction was in the quadrant of 45°, so it was ebbing and, when the current direction was in the quadrant of 225°, so the phase was flooding, showing an alternative and axial character in the currents of ebb and flood.

The fate the tide periods of flood and ebb are different classify the estuary as asymmetric according with Miranda et. al. (2002). The speed in the bottom showed a similar behavior to surface during the floods and large variations during the ebbs. Both currents speed didn't show relation with the salinity variation.

This estuary is homogeneous according with the diagram of Hansen & Hattray (1966). But, how can be seen, on the first hours of ebb, it showed a significant variation along water column and can therefore, based in this stratifications, be classified according with Pritchard (1955) as type B (partially mixed) in theses profiles. However, in most profiles during the sampling, the salinity was almost homogeneous along water column, even when it showed temporal variations. Therefore, in most of the study time, the estuary can be classified how well mixed.

Generally, the salinity was higher during firsts ebb profiles than during the flood phase. It is suggested that, cause the region is near the mangrove, the concentrated water of the mangrove caused for evaporation and soil absorption, is "polluting" the water layer, especially of the bottom, of the river during the ebb, and that cause Para river has great flow, this water more concentrated is diluted along ebb period, getting back to approximate the salinity of the surface.

Similar situation was observed for Lara and Dittmar (1999), in a tide channel of a mangrove near of Brangança, Pará's littoral, which inside tidal cycles, the water level and the salinity were inversely correlated (figure 13). During the ebb, the salinity had increase, reaching a maximum in low tide. During the flood, the salinity decreased due to water dilution of low tide by the less saline estuarine water, until a minimum of salinity was achieved in high tide (Lara & Dittmar, 1999).

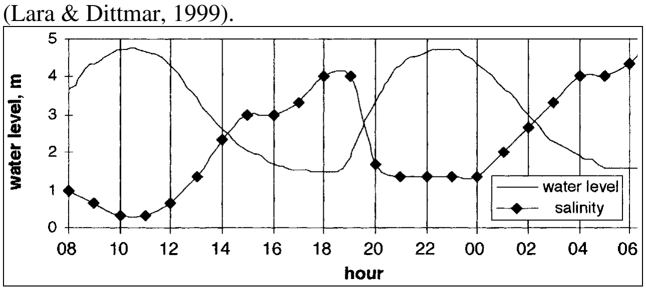

Figure 13: Relationship of salinity and sea level versus time in tide channel near Bragança, Pará's littoral. Source: Lara&Dittmar, 1999.

In relation to temperature, the larger records were during the day. These higher temperatures were caused probably for the higher incidence of sunshine on these hours. There is not an apparent relationship between the temperature of surface and the of bottom with the speed and direction of tide currents.

CONCLUSION

The wind showed more intense during the day, caused especially for movements of air masses consequent by higher temperature in this period (from 15:00 to 20:00 hs of 17/12/09 and from 09:00 to 15:00 hs, exception at 12:00, of 18/12/09), with hours of lull during the night (at 04:00 and 05:00 hs of 18/12/09).

According Baltazar (2010), the tide behavior in Colares island was waited because Colares is geographically downstream of the Mosqueiro island, thereby receiving, first and with more intensity the influence of tide. So, this way about the interaction between the tide wave propagating estuary above and the morphology of the estuary according Nichols and Biggs (1985 apud Dyer,1997) the estuary can to classify the Pará river estuary like hiposincrono, cause the high of the tide decreases along the estuary. And according Dalrymple et. al. (1992) the Pará river estuary is the type dominated by tide, because it is typically macrotidal and hiposincrono.

In relation to current, can to conclude that the determination of the velocity vectors of the estuarine system showed an alternative and axial character in the currents of ebb and flood, with orientation of 230º to 260º and 69º to 30º, respectively. The currents system of the lower estuary of the Pará river showed variations of direction and intensity bound mainly with the tide oscillations and the channel morphology.

The salinity in the estuary is strongly influenced by tide and, it is assumed, for surrounding environment, showed to be a somewhat peculiar, with the most of profiles showed homogeneity and salinity not very high, exception at the first hours of ebb, which were recorded values higher and profiles with stratification in water column.

The classification to salinity stratification according with the Pritchard (1955) is that the Pará river estuary showed like type B at the first hours of ebb and can be classified like partially mixed; however, in most of profiles during the sampling, the salinity was virtually homogeneous along water column and can be classified like well mixed.

According with the classification obtained through diagram of stratification-circulation of Hansen and Rattray (1966), for the study period, dry season, observed that the estuarine system of Pará river has characteristics of type 1 (well mixed) without vertical stratification.

The criteria of classification of estuary from variation of the salinity stratification in water column may change significantly between neap and spring and the periods of maximum and minimum of river discharge, therefore study more detailed is necessary, in different period of tide and river flow, to classify of a more comprehensive and effective the estuary studied.

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