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Forcing and mixing processes in the Amazon estuary: A study case

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Summary. — The research area of this paper is located at the estuary of the Amazon River (Brazil), more precisely at the river mouth (parallels 00° 30′ N and 1° 30′ N and meridians 049° 00′ W and 050° 00′ W). This paper presents the results of air movement analysis on the surface atmospheric circulation over the Mouth of the Amazonas River, salinity and temperature measures as well as measurements of currents, carried out along a longitudinal section in the navigation canal region of the Northern Bar of the Amazon River (Barra Norte do Rio Amazonas) in June 2006, during the river flood season in the quadrature tide. This paper purports to contribute towards better interpreting the dynamics effect in hydrodynamic, meteorological and hydrographical parameters at the river mouth. The conclusion drawn from an examination of the issues and related research is that: a) the saline wedge-type stratification can be seen approximately 100 km away from the mouth of the Amazon River during the end of the rainy season in the quadrature tide; b) probably, at Amazon estuary quadrature entrainment processes are predominant and are the ones responsible for increased salinity in surface layer, whereas turbulence scattering mixing is secondary to it. c) The large flow of fresh water from the Amazon River at the end of the rainy season implies the displacement of the front saline position over the internal Amazon continental platform. d) The tidal wave shows a positive asymmetry in the canal, with floods lasting less than the ebb tide. This asymmetry decreases towards the ocean, eventually becoming reversed in the presence of a saline wedge. The speeds, however, have a negative asymmetry, with more intense ebb tides, due to the river flow and is more evident by the existence of quadrature tides. e) The progressive behavior of the tidal wave in its propagation in the Northern Channel as well as the effect of morphology on the discharge were observed, with the canal configuration causing the first four anchoring points of the tide to propagate in a straight direction. f) The average climatology of the wind shearing vector shows that it is predominantly zonal over the Atlantic.

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g) The shearing intensification near the coastal area is according to the zonal wind intensification pattern. The Amazon estuary has unusual characteristics in relation to many established paradigms of estuarine physics; therefore, many more detailed studies are necessary to understand this system's turbulent processes.

PACS 47.27.-i – Turbulent flows.
PACS 47.27.tb – Turbulent diffusion.
PACS 47.80.Cb – Velocity measurements.
PACS 47.80.Fg – Pressure and temperature measurements.

1. – Introduction

This paper is part of the Hydrodynamics Modeling and Sea Level Monitoring of the Northern Bar of Amazon River (Modelagem Hidrodinâmica e Monitoramento do Nível do Mar da Barra Norte do Rio Amazonas—BARRA NORTE) project, as well as the Piatam Sea and Piatam Ocean projects. Such projects are conducted in order to promote a better environmental monitoring in the Northern Bar of the Amazon River. In the Northern Bar Project, navigability conditions are checked for security aiming at fewer accident risks, thereby seeking to reduce merchant transportation costs while working together to preserve the environment. Piatam Sea and Piatam Ocean projects aim at evaluating the potential environmental impacts of exploration, production, and transportation of oil and derivatives in the Brazilian Equatorial coastal and oceanic areas. This is a wonderful partnership between the productive sector and the scientific community in order to optimize the environmental management of Petrobras businesses in the Brazilian northern region.

The research area of this paper is located at the estuary of the Amazon River, more precisely at the river mouth, expanding to the Amazon platform region and is between parallels $00^\circ\ 30'$ N and $1^\circ\ 30'$ N and meridians $049^\circ\ 00'$ W and $050^\circ\ 00'$ W. This region is located in the northern part of Brazil (fig. 1). It covers an approximate area of 12 thousand square kilometers, supplied mainly by the discharge of Northern Canal of the Amazon River.

At the estuary there are several mechanisms that cause turbulence: influence of solid contours (estuary bottom and shores), speed vertical shearing (fluid inside), wind shearing stress (free surface) and surface and internal gravity waves. Turbulence intensity controls vertical distribution of estuary water mass property concentration. As flow into the estuary takes place during the transition or turbulent regimen, produced by small space and time scale movements, entrainment, turbulent scattering and advection are the processes responsible for fresh water mixing up with the sea and for local salinity variation, as well as for concentration of natural properties and man-made ones.

This approach presents the analysis results of air movement on the surface of the Amazon Mouth, salinity and temperature measures as well as the measurements of currents, carried out along a longitudinal section in the Northern Bar navigation canal of the Amazon River, in June 2006, during the flood seasons in the quadrature tide.

Based on the results, interpretations about both longitudinal and vertical variability of these parameters were made, relating the hydrographic parameters to the tide conditions, depths and river discharge and influence of wind shearing in the area of study.

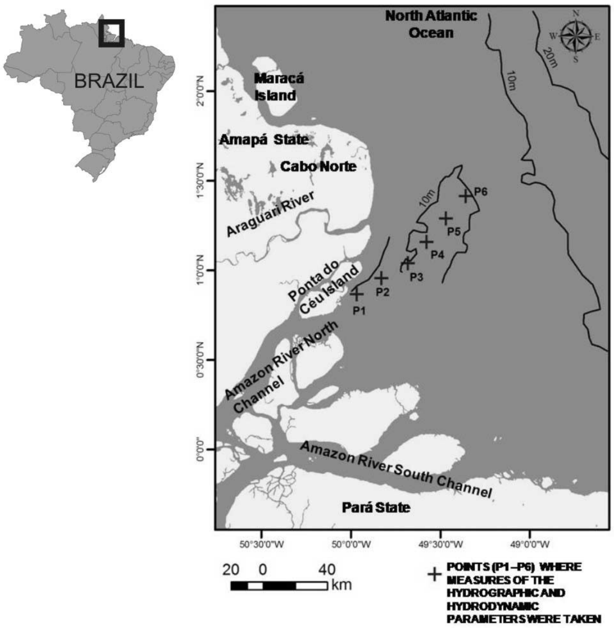

Fig. 1. – Geographical location map of the northern part of Brazil and location of the points where measures of the hydrographic and hydrodynamic parameters were taken.

2. – Environmental characterization of the area

At Amazon low estuary circulation and mixing process forcing mechanisms are semidiurnal macrotide; persistence of trade winds; and the large discharge of fresh water. It should be mentioned that sediment conveyance is important, Coriolis effect is weak since it is an equatorial zone, and friction with bottom can be more important than Coriolis acceleration.

In the case of the Amazon estuarine system, circulation and mixing are predominantly controlled by the variable contribution of water from the river [1].

In this region, the tide works like as a semidiurnal progressive wave [2] and spreads over the platform towards the river mouth, with reduced width and depth, forming an estuary with a convergent contour.

The Amazon River leads to the Atlantic Ocean an average flow of $\sim 170 \times 10^3\,\mathrm{m}^3/\mathrm{s}$, with a maximum flow in May/June and a minimum flow in November/December, thus releasing $\sim 1.2 \times 10^9$ tons of sediment a year on the platform [3]. A significant part of such sediments has been accumulated in the internal continental platform, forming an underwater delta [4]. Hence, there are large areas with high concentrations of fine sediment near the bottom [5], known as mudflows, which influence the friction dissipation.

Results from a numerical modeling prove the existence of tidal increase in the canal region, as a result of the convergence effect. However, the broad amplitudes of tides observed in the region (over 2 m in the quadrature tide) occur by the reduced friction at the bottom, caused by the presence of mudflow [6, 7].

The disturbance of the fluvial discharge by the tide is noticed by hundreds of miles upstream from the mouth [8], and the mixture of fresh water and salt water occurs at the continental platform [9].

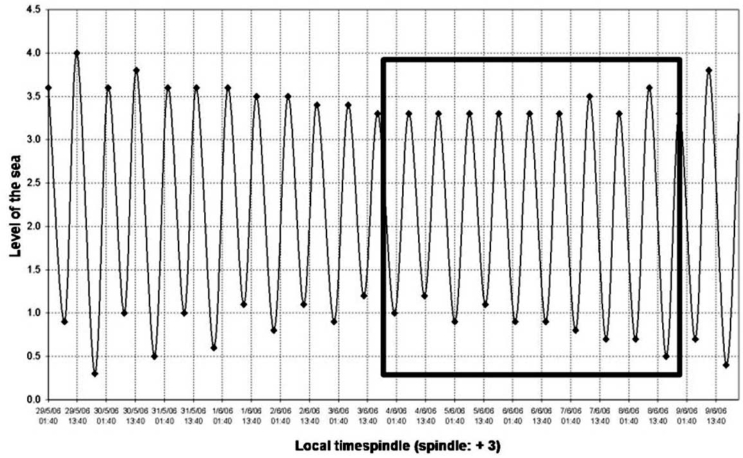

Fig. 2. – Tide forecast for Ponta do Céu, specifying the period when measures were taken. Source: Data from DHN Tide Tables, 2006.

The climate at the continental platform of the Amazon ranges from humid to superhumid, with yearly averages of pluviometric rainfall exceeding 2000 mm/year [10]. According to Köppen's classification, the climate in Af-type area of study, *i.e.* the dry season and the rainfall in the month when it rains less equals to or is higher than 60 mm.

Trade winds blow throughout the year on a platform where its influence is clear. According to Fontes [11], trade winds have a seasonal variation associated to the migration from the Intertropical Convergence Zone (ITCZ). ITCZ is preferably located in the Northern Hemisphere, migrating seasonally from near the equator in March/April, to approximately 5° N, in August/September [12]. Therefore, during Summer and Fall in the Southern Hemisphere, there is larger influence by northeast trade winds, with ITCZ located at the Amazon River mouth. On the other hand, in Winter and Spring in the Southern Hemisphere, southeast trade winds are prevailing, with ITCZ migrating northwards.

As a result of the local wind, shearing stress is highly important for the plume variability of the Amazon River. Winds flow almost parallel to the coast from June to November, with a speed of 10 m/s during the day and 14 m/s at night [13].

3. – Materials and methods

The field work was conducted in June 2006, during the flood season of the Amazon River (fig. 1), with quadrature tide. The plan of activities collected the data as listed: a) Salinity and temperature profiles; b) current measurement; and c) wind and shearing climatologic analysis.

The tide forecast data from the Ponta do Céu (Northern Bar) marigraph station arranged on the Tide Tables (fig. 2) provided by the Hydrography and Navigation Directors (Diretoria de Hidrografia e Navegação—DHN). Nevertheless, it was observed that the tide in the anchoring areas was significantly different from the forecasts for the selected marigraph station. This is a result of the tide dynamics that makes it impossible to relate the remote areas of the marigraph station. Thus, it was decided to monitor the

TABLE I. – *Latitudes and longitudes of the six anchoring points, where measures were taken. Global Positioning System (GPS/Garmin).*

Point	Latitude (degrees)	Longitude (degrees)
1	$00^\circ\ 52,06'$ N	$049^\circ\ 57,95'$ W
2	$00^\circ\ 57,42'$ N	$049^\circ\ 49,66'$ W
3	$01^\circ\ 02,38'$ N	$049^\circ\ 40,86'$ W
4	$01^\circ\ 09,49'$ N	$049^\circ\ 34,53'$ W
5	$01^\circ\ 17,45'$ N	$049^\circ\ 28,03'$ W
6	$01^\circ\ 24,99'$ N	$049^\circ\ 21,44'$ W

tide on the spot in order to collect water samples in different tide stages. The oceanographic profiles were conducted in the displacement towards the high seas of the Sirius Hydrographic Ship, owned by the Brazilian Navy. There were made six anchoring points along a section of approximately 90 km, where the hydrodynamic and hydrographic data presented here was collected (fig. 1). In these stations, data was collected. The measures were taken from 06/03/2006 to 06/07/2006. An image of the region under study shows the points where the measures were taken (fig. 1 and table I).

3˙1. *Salinity and temperature.* – At every station, the information about the samples of water collected, such as date, time, station number, latitude/longitude, local depth (m), temperature (°C) and salinity (ups) was collected concerning the samples of water collected. In order to obtain the water samples, a frog-type pump set to a cage was used. To measure the hydrographic parameters, an Orion conductimeter, model 115, was used.

The cage containing the frog-type pump was submerged by a winch (set at the ship bow aport). The pump withdrew water on the surface (in this study considered up to the depth of 1.5 m), in the middle and at the bottom, three times during the high tide, at the half flow tide or flood and at the low tide, at intervals of about three hours. In each of the six anchoring points, the procedure was repeated, except for point 2 because of a failure on the collection equipment.

The depths were obtained with the aid of echosounder equipment from the "Sirius" ship. In areas where depths were more pronounced, the number of water column samples exceeded three collections.

The salinity and temperature data was processed taking into account values and averages obtained in the water column vertical section of each anchoring point as a result of the tide stage.

3˙2. *Measures of currents.* – Level measures were taken based on the echosounder record and the speed intensity and direction of currents, where vertical speed sections were conducted by means of an ADCP (Acoustic Doppler Current Profiler) 600 kHz doppler manufactured by RD Instruments and calculating the average speeds and direction on an hourly basis. This piece of equipment was operated online in the ship's hangar on a continuous basis during the entire period of measurements (13 h per anchoring), on the right edge amidships.

The speed data was processed using a Matlab application by Mathworks in order to characterize the speed vertical section structure in the region. Vectors were not corrected by magnetic slope (20 degrees) and are referred to per magnetic North and geographic year.

3·3. *Surface atmospheric circulation analysis.* – In this paper, the wind field and wind shearing on the area of study is assessed for June by means of two databases very much used by the scientific community, namely: a) Re-Analysis ERA-40 Project distributed by the European Center for Medium-Range Weather Forecasts—ECMWF; and b) QuikSCAT Global Ocean Surface Wind products, distributed by NOAA CoastWatch Program and the NASA Jet Propulsion Laboratory. Documentation and further information may also be obtained from the PO.DAAC QuikSCAT Web site (`http://podaac.jpl.nasa.gov/quikscat/`).

The 43-year (1959-2002) set of *re-analysis* from the ECMWF was used to calculate the climatologic average of June, in a $2.5° \times 2.5°$ grid area (latitude *vs.* longitude). Data from QuikSCAT (monthly average) was used for a case study (C2006) specific to the month of June 2006. In this case, maps have a higher resolution due to data made available on the $0.25° \times 0.25°$ grid area. The wind shearing fields generated in the *re-analysis* and the satellite are at the N/m^2 unit.

4. – Results and discussions

4·1. *Salinity.* – Samples collected with the "frog" pump and measures with the conductimeter recorded a salinity of 0.0 ups or 21 mg/L in the first five anchoring points. The average values of salinity remained constant and equal to zero, even with the depth variation and different tide stages; see fig. 3. Therefore, these points can be classified as belonging to the River Tide Zone, *i.e.* they are the "fluvial part" with salinity practically equal to zero (0 to 2 ups), but still under the influence of the dynamic tide.

Only in the sixth anchoring point, salinity values different from of 0.0 ups were recorded, reaching values ranging from 0.1 to 18.6 ups with increased depth. The recorded values ranged slightly according to the tide stage. In the High Tide, the bottom salinity was 18.6 ups and the Low Tide was 14.1 ups, and the salinity difference was 4.5 ups, see fig. 3. This figure shows a vertical variation of salinity showing a well-identified stratification right on the first miles of water column; the salinity values varied, increasing with depth.

The sixth point, however, can be classified as belonging to a Mixing Zone, as it is a point located in a region where fresh water from the continental draining mixes with sea water.

This data confirms the remarks by Miranda, Castro and Kjerfve [14] for the area. These authors consider the mixing zone in the region with salinity rates below 10, usually found in estuaries characterizing the mixing zone, located, in this case, in the internal continental platform.

The higher salinity value found in the sixth anchoring point of this study was 18.6 parts per one thousand in the high tide, 13 feet away from the surface close to values found by Diegues [1] during the flood season, near the sixth anchoring point of this paper, with values of 14 parts per one thousand in depths close to 14 meters.

The salinity values observed in the sixth anchoring point of this study indicate the presence of a saline wedge in the region, confirming the results obtained by Limeburner and Beardsley [15,16], who conducted studies in the Amazon Platform area and found the existence of a saline wedge. The authors of the above-mentioned studies also realized that

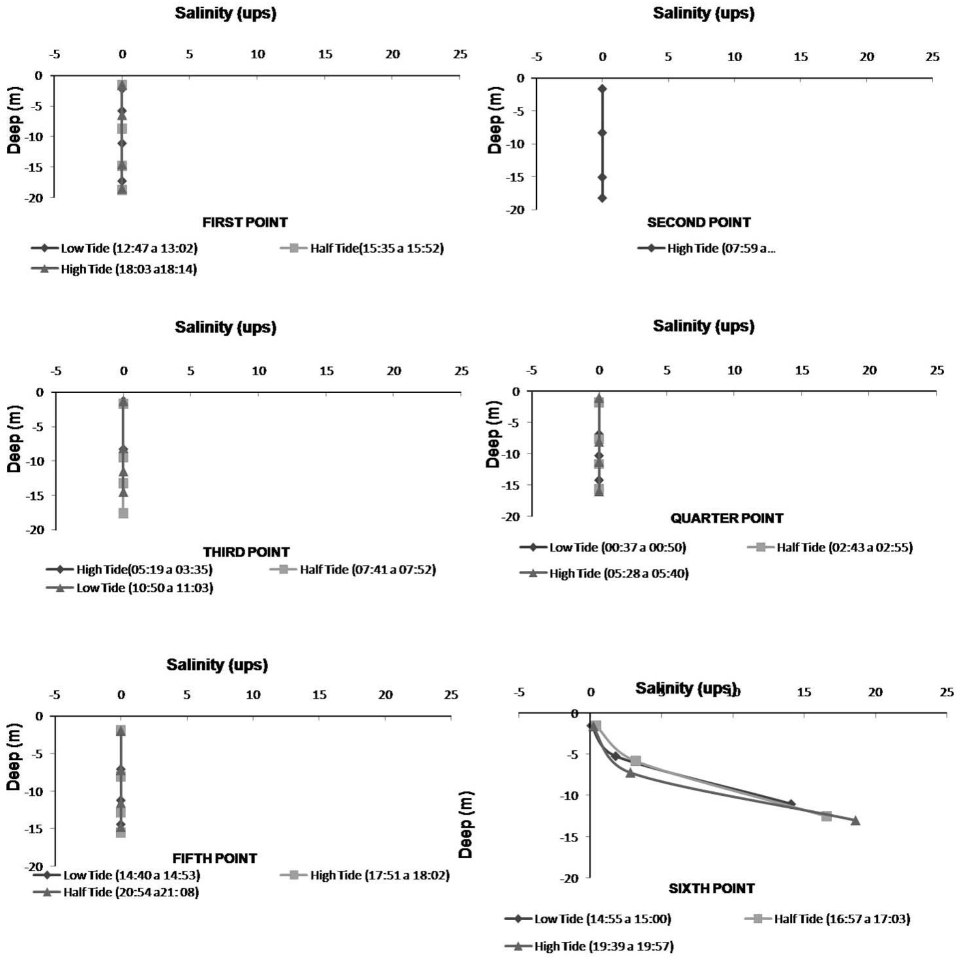

Fig. 3. – Charts containing the vertical salinity distribution for each of the six anchoring points at each tide stage of the Northern Bar in June 2006.

the saline wedge suffers a seasonal variation according to the maximum and minimum river discharge.

The sixth point from which salinity starts to be observed is located 90 km away from the mouth, which evidences the penetration of the Amazon river plume into the continental platform; such data also corresponds to those referred to by Patchineelam [17], which states that the saline wedge stratification was evidenced 120 km away from the river mouth in quadrature tides. This same author claims that the fluvial discharge has a much differentiated seasonal component, reaching at most $2.5 \times 10^5\,\mathrm{m^3\,s^{-1}}$ in May and at least $1.2 \times 10^5\,\mathrm{m^3\,s^{-1}}$ in November.

The Amazon River has a well-defined hydrological cycle, showing a difference two to three times larger between the flood season (May to July) and the drought season (October to December). By the time of this paper, June 2006, the river was in the flood period, as can be seen in fig. 4, with an approximate flow of $2.75 \times 105\,\mathrm{m^3/s}$.

The big flow by the river allows the introduction of fresh water preferably by the upper

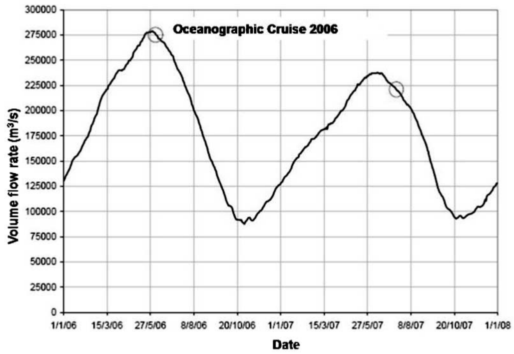

Fig. 4. – Hydrographs for the Óbidos station located approximately 800 km away from the mouth of the Amazon River.

layers with the retreat of the salt tide; this low-salinity plume can be found from the 11-meter isobath on the continental platform. This circulation shows a behavior similar to that found by Geyer *et al.* [5], with the extension of the Amazon River plume found from 10 m deep on with the distribution of salinity in the internal continental platform.

In times when deeper water was reached, with the tide variation (from low tide to high tide), there was average increased salinity for that point (fig. 3), due to higher salinity levels found at the bottom. This is probably due to the saline wedge displacement towards the river with the tide variation.

According to Officer [18], saline wedge estuaries have a vertical saline section with an intense vertical gradient halocline, the circulation is named after the fluvial discharge, the penetration is responsible for the slight rise of salinity at the superficial layer and the saline wedge movement upward from the estuary is slow. The saline structure observed in this data analysis indicates the process described above can be seen in the area of study, where the circulation is dominated by fluvial discharge. One can also observe that from point 1 to 5 there was only advection, and at point 6 mixing processes can be found primarily between 6 and 8 m deep, where penetration with sea water exchange from lower to higher layers.

Due to the remarkable river plume discharge on the platform, the tide—a dominant in macrotide region estuarine circulation—now has a secondary role, albeit not a negligible one, with quadrature amplitudes varying from 2 m for the site.

4˙2. *Temperature*. – The temperature data presented shows that the temperature values remained close, between 27.9 and 29 °C even after increased depth at each tide stage and the time lag (fig. 5). The decreased water depth with a variation of the tide stages has not had a significant temperature variation. At the most dramatic variation—the low tide—a difference of approximately 1 °C was found between the surface temperature and in the middle of the water column, therefore, along the entire section, pronounced temperature stratification was not found.

Such results corroborate those found by Limeburner *et al.* [16] which upheld that at the maximum discharge, the surface temperature values ranged from 28.5 °C to 29 °C.

In the six anchoring points, the air temperature was around 30 °C and the water temperature at the surface had an average value around 28 °C. The average temperature values in vertical distribution were also around 28 °C. Therefore, it can be verified the

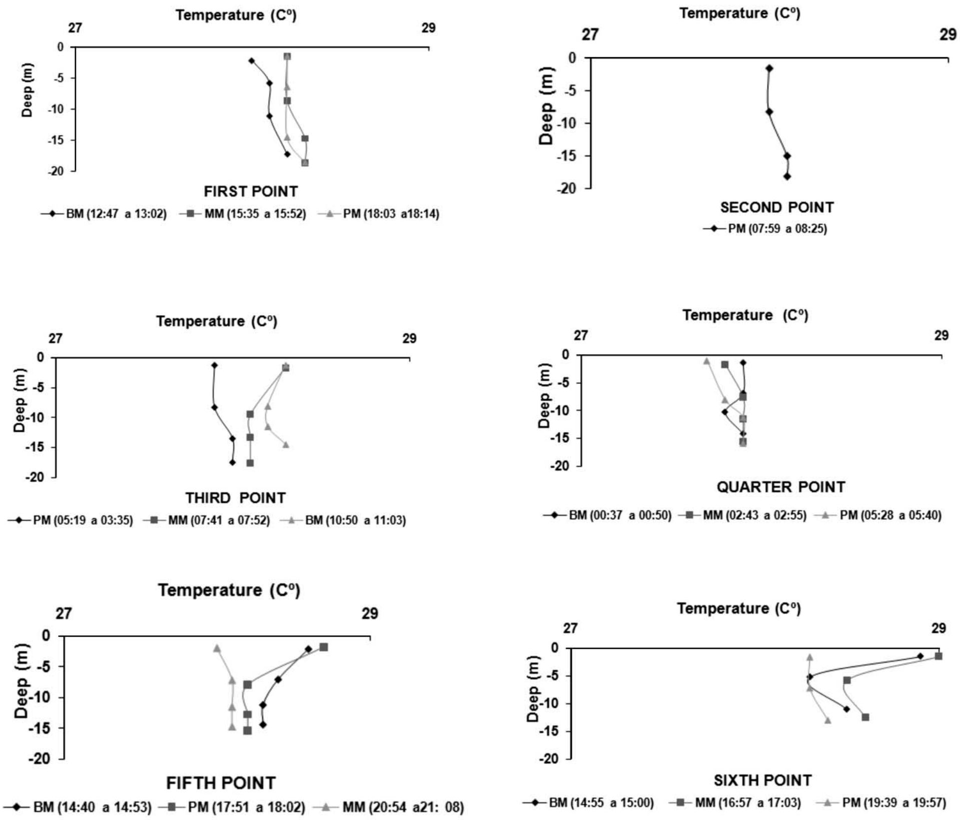

Fig. 5. – The temperature vertical temperature in the tide stages (low tide, half tide, and high tide) at each anchoring point of the Amazon River Northern Bar in June 2006.

temperature had uniform distribution both vertically and horizontally, which is usual in low-latitude areas, due to the small thermal oscillation in the region, where a homogeneous layer can be seen, which can be explained by the turbulent water process scattering heat throughout the water mass.

Comparing the salinity vertical distribution to the temperature vertical distribution, we can ascertain the temperature has varied a little with more depth while salinity varied more between the surface and the bottom. This data shows that density is determined primarily by the salinity distribution.

4·3. *Current measurement*. – Figure 6 shows average levels and intensities of speeds throughout the tide cycle in stations 1 to 6, as well as tide ellipses. The following remarks can be made from the collected data:

- The tide wave behaves as a progressive wave, but it has variations in the stage differences between levels and speeds also due to their relevant asymmetries.

- The current average speeds were always maximum at the ebb tide (positive values in fig. 6).

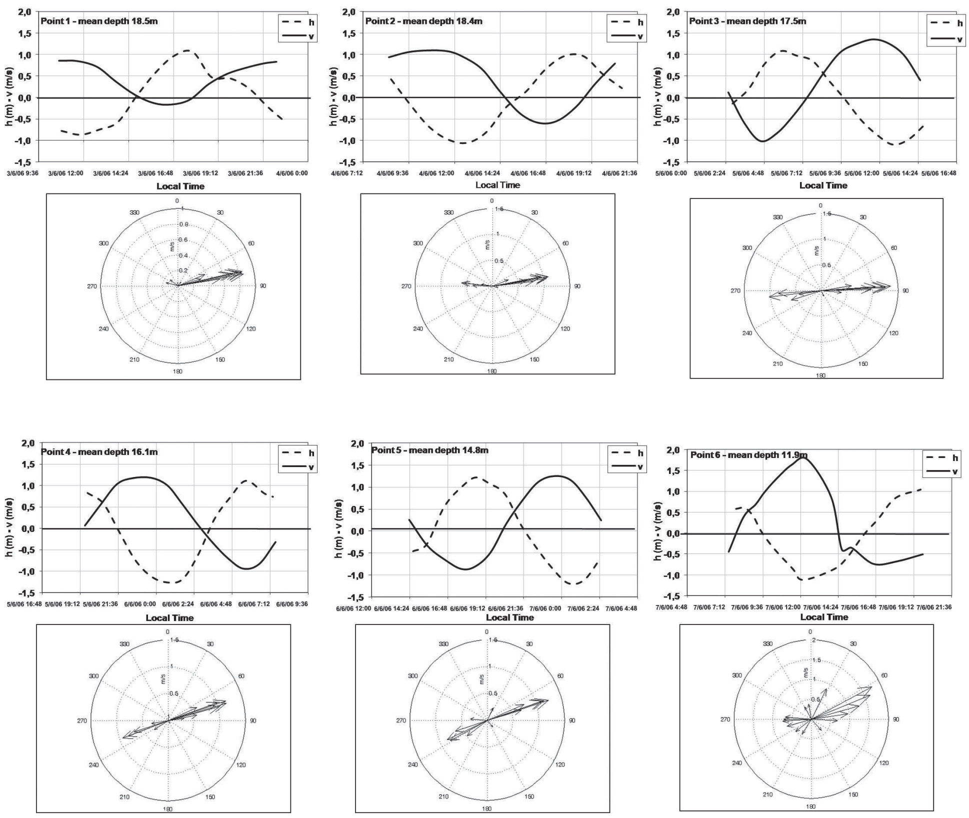

Fig. 6. – Average hourly values of speed levels and intensities (left) and tide ellipses (right) along the tide cycle in stations 1 to 6.

– The speed sections in points 1 to 5, where the presence of saline introduction was not checked, were relatively homogeneous, without significant variations towards the discharge.

– The maximum intensity recorded was on the surface in point 6, where the presence of saline salt front was recorded. At the flood time of the Amazon River and the quadrature tide, the saline front was detected approximately 90 km downstream from the mouth.

– In points 1 to 4, the tide is predominantly in a straight line, aligned with the canal direction. However, when discharge is no longer controlled in stations 5 and 6, there is a variation in the current direction of the section, forming the typical tide ellipses.

– From numerical modeling results for average river flows, the expectation was realizing that the maximum tide amplitude will take place in station 4. The data shows that the maximum amplitude occurs in station 5, which would correspond to a larger river flow. The short sampling period and errors in levels obtained from the echosounder record cannot be conclusive for that matter.

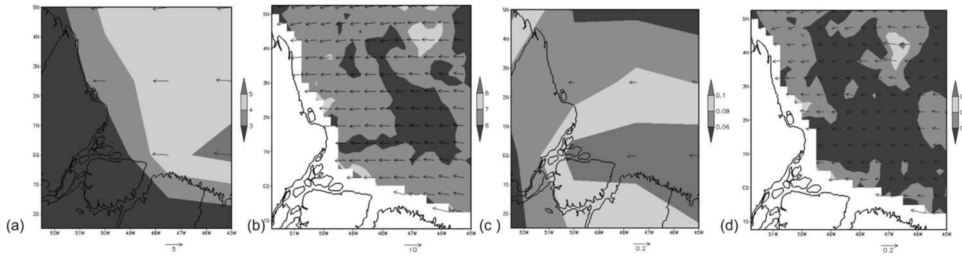

Fig. 7. – Wind field (m/s) in June over the area of study, climatologic scenario (a) and case study C62006 (b). Wind shearing field (N/m^2) in June over the area of study, climatologic scenario (c) and case study C62006 (d).

In such data, the tide penetration trend can be seen, as a result of both the dynamic tide and the saline tide. From points 2 to 5, including these ones, the hydraulic behavior is influenced by the tidal dynamics; in point 6, the saline tide is already in operation, where saline introduction and mixing conditions between fresh water and salty water by penetration was found.

This behavior by the local tide is related to several determining factors, such as: a tide large amplitude, a large river flow, the canal morphology, and the high concentration of fine sediments at the bottom.

4·4. *Surface atmospheric circulation analysis*. – Despite the low spatial resolution, the climatology at the European center (fig. 7a) shows, as expected, reduced wind intensity between the oceanic surface and the continent, in the area of study. Prevailing wind direction, from the East, obtained by QuikSCAT (fig. 7b) is consistent with that obtained in climatology. The potential causes of different wind satellite-obtained intensities, in relation to climatology will not be dealt with in this paper, as they are beyond its scope.

The average climatology of wind shearing vector (fig. 7c) shows that it is predominantly zonal over the Atlantic. This result was also expected, as a result of the predominant wind from the East. Another consistent result is the shearing intensification of the coastal zone, following the zonal wind intensification pattern. The results of case study C62006 (fig. 7d) show satisfactory consistency with climatology, without taking the intensity difference into account, as mentioned above. An interesting result, noticed from the wind shearing monthly average, is the intensification located in northern part of the map. This result is more evident in case C62006 due to higher spatial resolution reached by satellite.

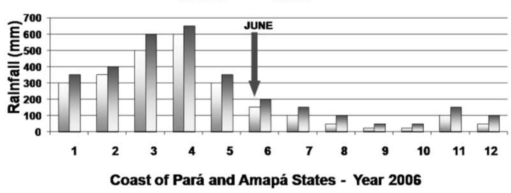

Fig. 8. – Rainfall Histogram for the coast of Pará and Amapá states regarding the year 2006.

4·5. *Rainfall.* – The Rainfall Histogram as accumulated in the year 2006 for the coast of Pará and Amapá states is represented in the graph depicted in fig. 8.

As to the assessment month of hydrographic parameters (June), rainfall was at least 100 mm and at most 200 mm, with a deviation on rainfall values expected for that corresponding month.

5. – Conclusions

The following conclusions resulting from this paper are presented below.

In the region, a spatial variability was identified, both vertically and lengthwise in salinity and conductivity levels during the quadrature tide. In points 1 to 5, the recorded salinity figures were equal to zero and the effects of the tide daily variations were easily noticed, and this leads to confirm that this area can be classified as River Tide Zone. Point 6 represents an increase in salinity and conductivity values, with increased depth of the quadrature high tides.

Temperature values did not have large spatial variations (being around 28 °C) for half a tidal cycle even after increased depth, following patterns presented by low-latitude areas.

The data proves that density is determined primarily by salinity distribution.

The saline front position, in the quadrature tide, in the rainy season, was located only near the sixth $\sim$ 90 km downstream from the river mouth.

The entrainment of halocline towards the platform is probably due to the river discharge strength of the Amazon River.

The effect of fluvial discharge constantly added by the river shall yield an estuarine circulation component that shall naturally displace the fresh water plume out of the estuarine basin geomorphologic limits and shall only dilute sea water at the Amazon Continental Platform. This phenomenon causes Mixing Zone displacement from inside the estuary to the Amazon Continental Platform and mixing of fluvial water to high salinity oceanic water mass takes place in the Coastal Zone, *i.e.* fresh water throughout this region of the river, salt water or mixed water is in the ocean.

The saline front moves slightly towards the mouth and retreats after the tide decreases, and this can be explained by increased salinity after the tide rises.

The estuary can be classified as highly stratified or salt wedge, as the salinity of surface waters is quite lower than the salinity of water at the bottom, which creates a pronounced difference in the vertical salinity section.

The difference in the vertical salinity profile, showing the current is moving in the opposite direction (river fresh water and salty water brought by the tide). In this scenario, speed shearing at the interface produces interfacial friction stress that, from the entrainment process carries portions of water from the sea to the upper part. Therefore, probably, at Amazon estuary quadrature entrainment processes are predominant and are the ones responsible for increased salinity in surface layer, whereas turbulence scattering mixing is secondary to it.

The large river flow allows the introduction of fresh water preferably by the upper layers with the retreat of the saline tide. This low-salinity plume is found from the 11-meter isobath on at the continental platform.

Due to the remarkable river plume discharge on the platform, the tide—a dominant in macrotide region estuarine circulation—now has a secondary role, albeit not a negligible one, with quadrature amplitudes varying from 2 m to 90 km from the mouth. It is important to point out that tide-induced mixing processes determine saline front position and structure.

The interpretation of current data related to those of salinity presented here showed the penetration behavior of the tide is due both to the dynamic tide and the saline tide. From points 1 to 5, the hydraulic behavior is influenced by the tide dynamics; in point 6, the saline tide is already in operation where the saline introduction was found.

The tidal wave shows a positive asymmetry in the canal region, with floods lasting less than the ebb tide. This asymmetry decreases towards the ocean, eventually becoming reversed in the presence of a saline wedge. The speeds, however, have a negative asymmetry, with stronger ebb tides, due to the river flow and are even more evident by the existence of the quadrature tide.

The progressive behavior of the tidal wave in its propagation in the Northern Channel (Canal Norte) as well as the effect of morphology on the discharge were observed, with the channel configuration causing the first four anchoring points to the tide to propagate in a straight direction.

The prevailing wind direction, from the East, obtained by QuikSCAT, is consistent with that obtained in climatology.

The average climatology of the wind shearing vector shows it is predominantly zonal over the Atlantic.

The shearing intensification near the coastal zone follows the zonal wind intensification pattern.

The local wind shearing stress is highly important for the plume variability of the Amazon River; however, in this study, the data obtained so far cannot be conclusive for that objective.

The Amazon estuary has unusual characteristics in relation to many established paradigms of estuarine physics; therefore, many more detailed studies are necessary to understand this system's turbulent processes.

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