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THE M_2 AND M_4 TIDES IN THE PARÁ RIVER ESTUARY

Yuri Onça PRESTES[1*]; Alex Costa SILVA[1]; Marcelo ROLLNIC[2]; Renan Peixoto ROSÁRIO[2]

[1]Departamento de Oceanografia; Universidade Federal de Pernambuco, Brasil. E-mail: y.prestes@hotmail.com , alexsilvaufpe@gmail.com
*Autor correspondente

[2]Universidade Federal do Pará. E-mail: rollnic@ufpa.br, renanpeixoto@ufpa.br

RESUMO. O estuário do rio Pará representa um sistema complexo e peculiar, com processos físicos de micro e mesoescala gerados por forçantes de diferentes fontes (por exemplo, as marés astronômicas e a descarga fluvial). No presente estudo, as principais componentes semidiurna (M_2) e de água-rasa (M_4) são analisadas para quantificar graus de distorção e identificar assimetrias no estuário do rio Pará. Dois medidores de maré foram fundeados. Um na margem direita (ponto #RG) e outro na margem esquerda (#LF), durante 6 meses (Setembro de 2014 à Março de 2015). Além disso, foram utilizadas cartas harmônicas da Fundação de Estudos do Mar (FEMAR). Variações laterais foram identificadas entre #RG e #LF de acordo com as cartas cotidais de amplitude e fase, com defasagem de aproximadamente 10 minutos e variação de 2 cm na amplitude. Verificamos que a onda de maré entra pelo sistema pela margem direita (#RG). Os resultados indicaram graus de distorção maiores que 10% e assimetria positiva da onda de maré, sendo que a atenuação da maré no estuário pode ser maior que 400 km estuário acima ao longo da bacia de drenagem.

Palavras-Chave: Distorção de maré, Assimetria de maré, Componentes de maré, Variações laterais.

ABSTRACT. The Pará River estuary is a complex and special system in amazon continental shelf, with micro and mesoscale physical processes generated by forces of different sources (e.g., astronomical tides and river discharge). In this study, the main semidiurnal (M_2) and the overtide (M_4) components were analyzed by quantifying distortions degrees and identifying tidal asymmetries in the Pará River estuary. Two submersible tidal gauges were moored to measure the water level. One on the right margin (point #RG) and another on the left margin (#LF) recorded measurements 6 months (from September 2014 to March 2015). Furthermore, we used harmonic charts from Marine Studies Foundation (FEMAR, Fundação de Estudos do Mar). Lateral variations were also identified between #RG and #LF points from the amplitude and phase cotidal charts, with about 10 minutes delay and variation of 2 cm in tidal amplitude. We verified that the tidal wave enters in system by the right margin (#RF). The results show distortion degrees higher than 10% and positive asymmetry of the tidal wave in the Pará River, and the tidal attenuation in the estuary may be greater than 400 km upstream along the drainage basin.

Keywords: Tidal distortion, Tidal asymmetry, Tidal components, Lateral variations.

INTRODUCTION

The Amazon shelf is an atypical and highly dynamic environment. In this context, the Pará and Amazon rivers are widely studied and present an intense fluvial contribution, representing over 30% of all fresh water discharged into the Atlantic Ocean (Dai and Tremberth, 2002). The annual average discharge of this system is approximately 180,000 m^3s^{-1} (Masson and Delecluse, 2001; Oltman, 1968; Richey *et al.,* 1989). Despite it Amazon River magnitude, the Pará River represents a water body of large extensions, and need more attention by scientific community, mainly in unresolved oceanographic questions.

The Pará River liquid discharge is one order smaller than Amazon River, *i.e.*, approximately 104 m^3s^{-1} (Prestes *et al.,* 2014), with over 300 km of longitudinal extension with a mouth that is approximately 60 km wide. This river does not have a source *per se*, formed from the Bocas Bay, southwest of the Marajó Island, where it receives contribution from Amazon River through small channels called "Breves Straits" (Callède *et al.,* 2010). The Tocantins River is the main tributary of Pará River, which also receives water from the others smallest rivers. The Pará River can be classified as a large tropical estuarine system. In addition to high discharge, highlighted by several authors (e.g. Beardsley *et al.,* 1995; Gabioux *et al.,* 2005; Gallo and Vinzon, 2005; Geyer *et al.,* 1996; Le Bars *et al.,* 2010), tidal effect is the main forcing which acts on the Amazon continental shelf, with strong oscillations in semidiurnal, diurnal, and fortnightly tidal frequencies.

In large estuarine systems, lateral variability should be highlighted due to its importance in the physical transport processes and horizontal patterns of instantaneous and residual flow velocity (Cárceres *et al.,* 2003; Valle-Levinson *et al.,* 2000). Tidal currents and water level variations can provide lateral differences in large estuaries. Water level observations on both margins were analyzed in this paper in order to verify lateral variations in the estuary. To contribute to this discussion about horizontal differences, cotidal charts of amplitude and phase of the main semidiurnal component (M_2) will also be presented. Harmonic analyses were applied to the water level data to investigate the influence of astronomical tide upstream of Pará River estuary, and the lateral variation of the water level, as well as tidal wave distortions and asymmetries.

The pure components of the astronomical tide (e.g. M_2, S_2, K_1, O_1) cooscillated in shallow-water affecting each other. The oscillation in a confined channel of the estuary leads to nonlinear interactions between the main constituents with strong overtides effect (Friedrichs and Aubrey, 1988; Li and O'Donnell, 1997). In this study, the main semidiurnal (M_2) and the overtide (M_4) components were analyzed by quantifying distortions degrees and identifying asymmetries upstream in the Pará River estuary.

Recently, the interest in oil and gas exploration increased on the Amazon shelf, and possible threats to the environment should require more scientific background and studies. As the Pará River estuary presents strong physical process, this study will contribute to better understand the hydrodynamic generated by astronomical tides. Moreover, in case of accident involving oil or gas, the high turbulence mixing caused by the dynamic tidal effects represents several risks to estuarine ecosystems and drainage basin (Prestes, 2016), covered by mangrove forests and mud plains.

This manuscript is organized as follows: section 2 will describe the study area, methods of acquisition data, and processing. We present the results and discussion in section 3, based on analysis of lateral variability as identified by the time series variation of the water level, distortion, and asymmetry processes of the tidal wave. Conclusions and future perspectives are presented in section 4.

MATERIAL AND METHODS

STUDY AREA

The Pará River estuary is formed from the Bocas Bay, where it receives a part of water from Amazon River through the Breves Straits. Then, it gets the total discharge contribution of the Tocantins River and other tributaries, toward the Atlantic Ocean. The river has approximately 300 km of longitudinal extension (Fig. 1). The study area is inserted into the mixing zone of the Pará River estuary (Baltazar *et al.,* 2011; Bezerra *et al.,* 2011; Rosário *et al.,* 2014), where the oceanic seawater is measurably diluted by extensive drainage of the amazon continental system (Miranda *et al.,* 2002). However, the present study focuses only on dynamic tidal effects on the estuary.

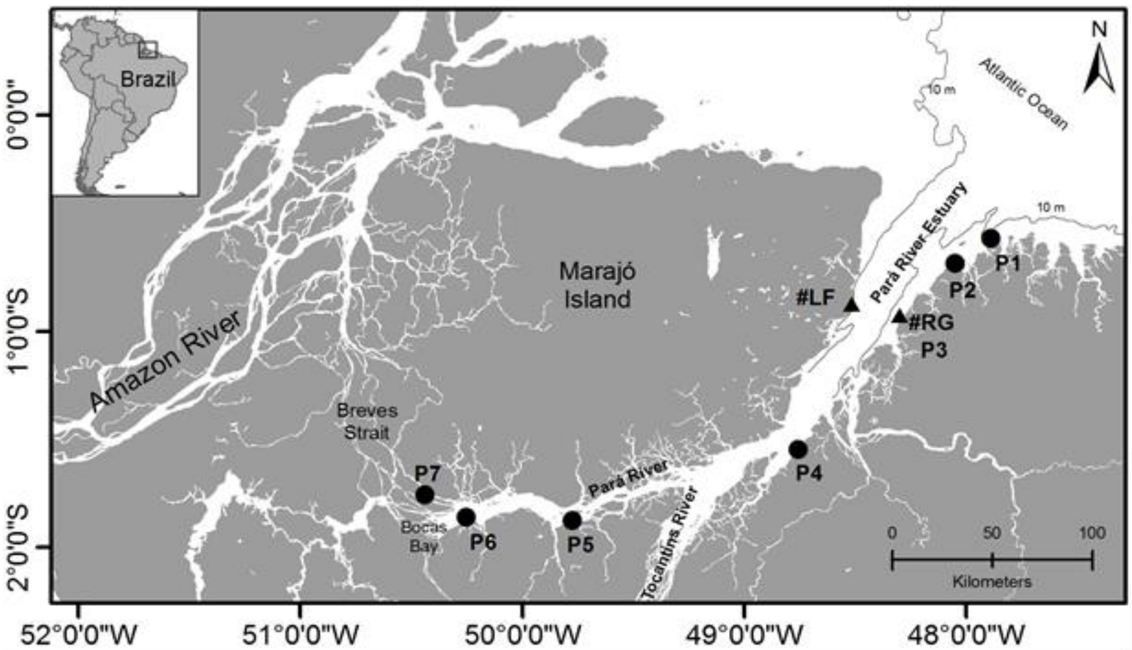

Figure 1. Map of the study area showing the Pará River estuary and some adjacent physiography. The points of tidal gauges are displayed (#RG and #LF, black triangles), as well as the location of the FEMAR stations (black circles).

DATA ACQUISITION AND PROCESSING

Tidal gauges were moored to measure the water level in the right margin (point #RG – Lat: -0.934161 / Lon: -48.297180) and in the left margin (point #LF – Lat: -0.881452 / Lon: -48.507270), represented by black triangles in Fig. 1. Sensors recorded measurements every 15 minutes for 6 months (from September 2014 to March 2015). We have also used harmonic charts from Marine Studies Foundation (Fundação de Estudos do Mar – FEMAR, 2000), duly presented by black circles in Fig. 1, covering the mouth nearby locations such as well in the estuarine upper regions, upstream and downstream of #RG and #LF points.

The main semidiurnal (M_2) and overtide (M_4) components were obtained by harmonic analysis of the time series of water level (#RG and #LF). This analysis considers the wave as the result of a sum of components represented by sinusoidal functions with constant amplitude and phase for each site (Emery and Thomson, 1998). These amplitudes and phases are determined from tide gauge records, which are adjusted for a least square fit resulting in harmonic tide constants. The assumption is that the answer to the driving forces does not change over time, representing the local tidal regime (PUGH, 1987). The theory of astronomical tide is shown in detail in specialized texts, such as Macmillan (1966), Harris (1981) and Pugh (1987). The package T-Tide v1.1 of the MATLAB® platform (Pawlowicz *et al.,* 2002) was used in the current study. This choice was based on the operational functionality of this tool. Furthermore, the regional model "OTIS Regional Tidal Solutions" was used to generate a map of the tide elevation and phase.

RESULTS AND DISCUSSION

TIME SERIES AND HARMONIC ANALYSIS

The time series of water level in both margins of the Pará River estuary clearly show a semidiurnal meso- and macro-tidal pattern, with maximum heights equal to 4.2 m. The mean variation between spring and the neap tide is 0.5-1.2 m, with a minimum height of the neap tide level about 2 m. The tidal wave delay between the margins was about 10 minutes, i.e., high tide occurs in #RG before the #LF point. Fig. 2 shows the water level variation and lateral delay.

The harmonic analysis quantifies amplitude and phase of the main tidal components in the estuary. The Tab. 1 and the Fig. 3 present the results of this analysis, highlighting the relationship between semidiurnal and quarti-diurnal components. Among the pure harmonic constituents (e.g. semidiurnal and diurnal) are displayed M_2, S_2, O_1, and K_1. These constituents are those with the greatest significance at the time of the tidal wave amplitude. The overtides components most representative were M_4 and MS_4, the result of interactions of the two major semidiurnal components shown in Tab. 1 and Fig. 3 (M_2 and S_2). The sum of the amplitudes of the M_2, S_2, O_1, and K_1 represents about 60% of the total tide amplitude (energy) in the Pará

River estuary region. The M_2 amplitude is one order of magnitude greater than M_4 component, with maximum values of 1.9 m and 0.07 m respectively.

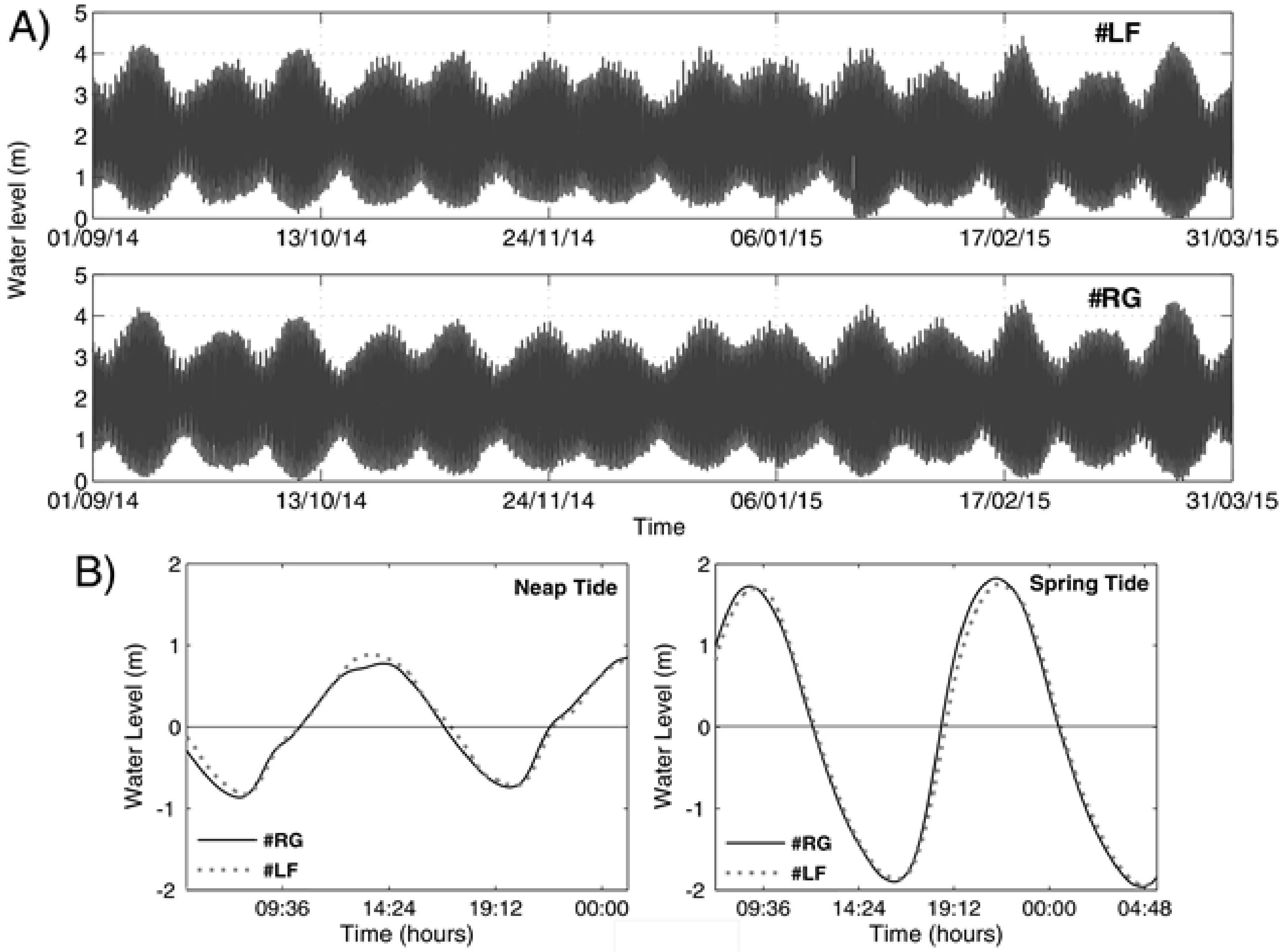

Figure 2. Time series of water level for Pará River estuary. A) Complete level as standard with six months of measurements (in days/months/year) from September 2014 to March 2015 on both margins (#RG - lower graph and #LF - upper graph); B) Level variation in a neap tide (left graph) and spring tide (right graph) conditions, along some day in time series.

Table 1. Amplitude, period, and phase of the main diurnal, semidiurnal, and quarti-diurnal constituents obtained through harmonic analysis.

Species	Constituents	Amplitude (m)	Period (h)	Phase (degrees)
Diurnal	K_1	0.10	23.93	62.87
	O_1	0.09	25.81	51.42
Semidiurnal	M_2	1.29	12.42	200.55
	S_2	0.39	12.00	222.93
Quarti-diurnal	M_4	0.07	6.21	351.84
	MS_4	0.05	6.10	347.82

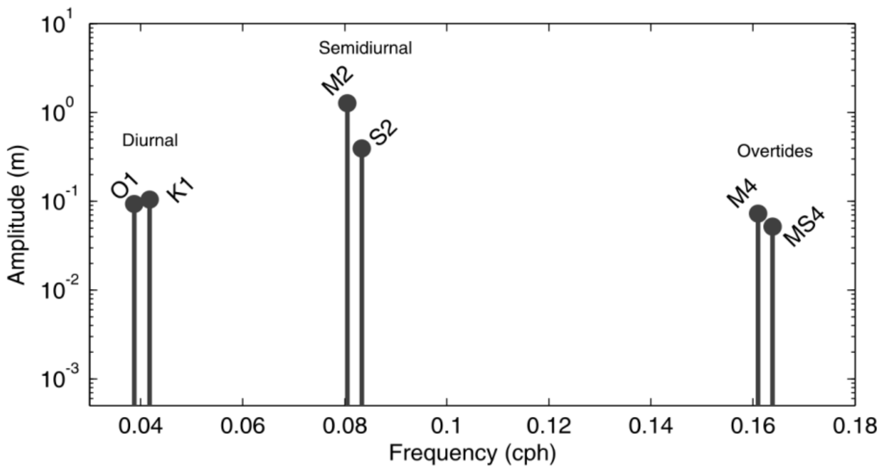

Figure 3. The relative amplitude of the main diurnal (K_1 and O_1), semidiurnal (M_2 and S_2), and overtides (M_4 and MS_4) constituents. Note that the tercidiurnal components are not displayed in this study. However, they oscillated with frequencies between 0.119 - 0.126 cycles per hour (cph) in the x-axis.

The values shown in Tab. 1 and Fig. 3 for the amplitude of the components are related to right margin (#RG); note that the components of #LF point do not appear due to a small difference. The amplitudes difference of the M_2 and M_4 components are approximately 2 cm between the margins.

The investigation of the relationship between the main semidiurnal tide constituent and the main overtide constituent generated important results about the dynamics of the mixing zone of the Pará River estuary. The intense fluvial contribution combined with cooscillation of astronomic tides, in an environment of large extensions. It certainly produces a different hydrodynamic standard and complex mixing process. The study area is localized at 60 km away from the mouth, but the tidal wave features a meso-macrotidal pattern (see Fig. 2) and high amplitude for M_2 component (Fig. 3). As it was found in the Amazon River estuary the importance of M_4 (Gallo and Vinzon, 2005), this overtide was also considered a shallow-water component of greater tidal significance in the Pará river estuary.

LATERAL VARIATION OF WATER LEVEL AND TIDAL PROPAGATION

The goal of this study is to investigate the tidal wave distortion processes and lateral heterogeneity through the analysis of time series of water level variation and results of the main semidiurnal and overtide components. The results shown in Fig. 2B exhibit approximately 10 minutes delay between the margins, with the coming tide primarily on the right margin (point #RG). Although commonly tidal analysis occurs in an upstream longitudinal way (Gallo and Vinzon, 2005), a 10 minutes delay and a mean difference in the amplitude of 2 cm verified laterally is a differentiated process. There is more than 25 km between the two measuring water level stations. Such spatial dimensions, associated with tidal currents and intense flow generated by river discharge interact with the complex bathymetry of the Pará River estuary (Gregório and Mendes, 2009). The comparison between the semidiurnal and overtide components demonstrates the increase in the distortion of the tidal wave upstream and reduction of the magnitude of M_2, as shown in Fig. 4, which displays the cotidal chart of M_2 amplitude and phase in the Pará River estuary.

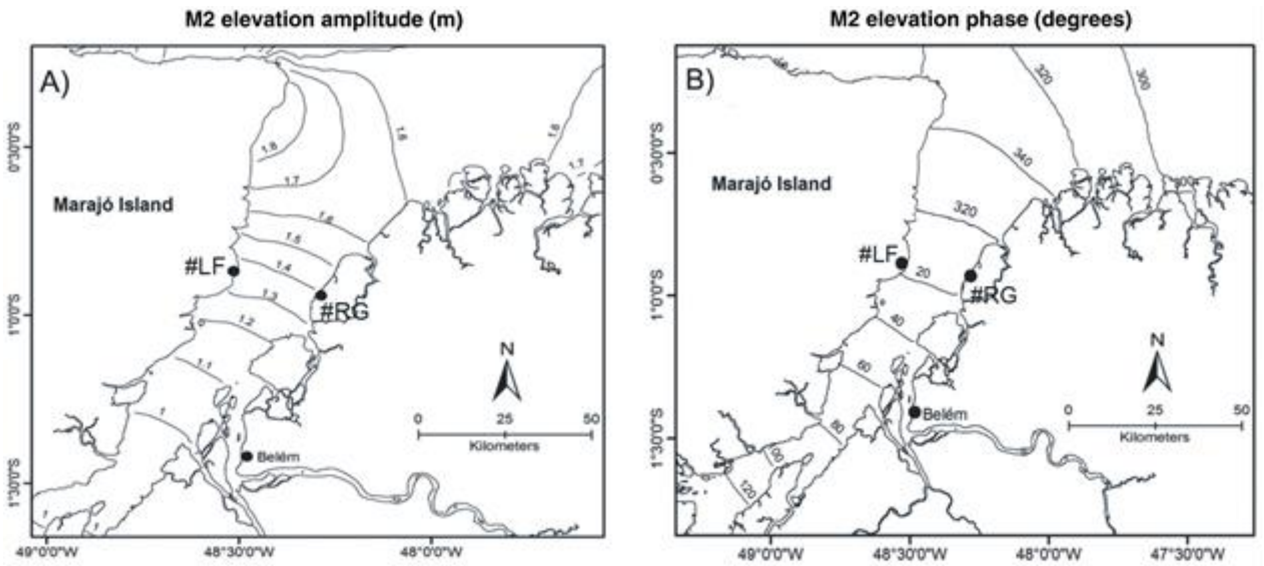

Figure 4. M_2 cotidal chart for amplitude and phase for the Pará River estuary (OTIS Solution Regional Tidal). A) M_2 elevation amplitude (m) and B) M_2 elevation phase. The black circles represent the tidal gauges location (#RG and #LF).

In the time series of water level, the cotidal charts also showed differences between the margins in #RG and #LF points, referring to the water level measurements. The results generated by the model of the cotidal charts corroborate the results of the water level stations with small differences of the order of hundredths lateral difference. However, the position of #RG and #LF points explains a 10 minutes delay and variation of 2 cm in tidal amplitude (see Fig. 4). The delay occurs due to a difference of 0.17° in M_2 phase between #RG point (Tab. 1) and #LF point (not shown). Beardsley *et al.* (1995), Gabioux *et al.* (2005), and Le Bars *et al.* (2010) used tidal models in the amazon shelf and identified the predominant of the semidiurnal M_2 component in this region, as observed throughout the Pará River estuary. These results are consistent with the analysis of the amplitude and phase shown in Fig. 3.

THE M_2 AND M_4 TIDAL ANALYSIS: STATISTICS, DISTORTION, AND ASYMMETRY

According to some relations amongst the two main semidiurnal constituents found (M_2 and S_2), it is possible to calculate some local tidal statistics (Kjerfve, 1990). For example, the mean tidal variation ($2.2 \times AM_2$) is 2.81 m, the ebb-tidal variation ($2 \times [AM_2 + AS_2]$) is 3.34 m and finally, the quadrature variation ($2 \times [AM_2 - AS_2]$) is 1.76 m. With the values found for the main diurnal and semidiurnal components, it is also possible to compute the tidal form number (Defant, 1961), given by: Nf = $[AK_1 + AO_1] / [AM_2 + AS_2]$. At the #RG point in the mixing zone of Pará River, the form number is 0.11 that confirms a semidiurnal tidal regime.

Based on the relationships between M_2 and M_4 amplitudes and phases, such as the relative phase calculation ($2x\ \theta M_2 - \theta M_4$) and amplitude ratio ($AM_4 / AM_2$), it is possible to perform an analysis of the tidal wave distortion and asymmetries (Friedrichs and Aubrey, 1988; Speer and Aubrey, 1985). The relation between amplitudes of components of M_2 and M_4 (AM_4 / AM_2) demonstrated that overtide is about 5.7% distortion of the tidal wave, indicating a mild distortion. According to George (1995), the distortion of the wave generates tidal currents and energy loss due to friction with the bottom in shallow environments, so that distortions are greater when these waves reach sheltered locations such as estuaries. Thus, as the present study surveys occurred in the mixing zone, the tidal distortions certainly increase upstream. This was verified by Prestes *et al.* (2014), in which the amplitude of the M_4 came close to 10% of the amplitude of M_2 and ($2x\ \theta M_2 - \theta M_4$) < 180° (*i.e.*, positive tidal wave asymmetry). Displaying increasing the degree of distortion in regions upstream of the study area, 150 km from the mouth of the Para River estuary.

The relative phase of this study also indicates positive tidal wave asymmetry, about 45.5°, with ($2 \times \theta M_2 - \theta M_4$) < 180° and flood times shorter than ebb teams. These effects are a product of non-linear transfer of energy and momentum of the main harmonic components (Cartwright, 1967; Friedrichs and Aubrey, 1988; Parker, 1991; Speer and Aubrey, 1985).

In order to expand the knowledge about the tidal wave distortion upstream in in the Pará River estuary, the FEMAR amplitude values for M_2 and M_4 components were adopted. Tab. 2 shows the values found for these amplitudes and the locations of the measuring stations.

Table 2. M_2 and M_4 amplitude and distortion analysis according to harmonic charts of FEMAR (2000) and of tidal gauge (#RG point). The location of the points are: P1 – Guarás; P2 – Taipu; #RG/P3 – Colares; P4 – Porto de Vila do Conde (Barcarena); P5 – Curralinho; P6 – Baía das Bocas e; P7 – Breves.

FEMAR station	M_2 amplitude (m)	M_4 amplitude (m)	M_4 / M_2 (%)
P1	1.31	0.06	4.64
P2	1.57	0.09	5.70
P3/#RG	1.29	0.07	5.91
P4	1.08	0.13	12.21
P5	0.54	0.03	7.01
P6	0.47	0.04	9.09
P7	0.50	0.05	10.6

The results obtained for the indicators of the tidal wave distortion degree exhibited maximum value with AM_4 / AM_2 = 12.21%, in a region of the Pará River estuary that undergoes the channel constriction effect (point P4, Fig. 1). Note that the distortion values increase upstream, as well as the M_2 amplitude decreases as the tidal wave is attenuated due to friction with the bottom and the margins. However, the amplitude of the M_4 only varies more clearly at P4 (see Fig. 1), with channel constriction effect. Therefore, the verified distortion effect does not occur because of the increased range of M_4 (due of the friction effect in shallow waters), but due to the tidal wave attenuation upstream and consequent decrease of the semidiurnal M_2 component amplitude.

CONCLUSION AND FUTURE PERSPECTIVES

- The Pará River estuary is a complex and peculiar tropical system with physical processes of micro-mesoscale generated by forces from different sources (e.g. astronomical tides and river discharges). This is an estuarine system with great importance in amazon shelf. In addition to the intense input of the river discharge of 10^4 m^3s^{-1} the estuary of the Pará River is subject to cooscillation the astronomical tide with macrotidal coastal regimes.

- According to how the tidal wave oscillates and enters in the estuary, it gradually occurs the decrease in amplitude due to attenuation of the tidal wave, producing intermediate regions under the mesotidal regime and upstream sites with a microtidal regime.

- There is a predominance of semidiurnal variations in the mixing zone of the Pará River estuary, with the secondary importance of the diurnal oscillations (both astronomically pure) and overtides components, generated due to non-linear interaction among the main harmonic constituents, especially the M_4.

- The comparison between the margins showed that there is lateral differentiation along the flood and ebb stage caused by the tide. The fast entry of the tide in the right margin (point #RG) suggests that the mixing processes depend not only on the seasonal variability of the river discharge and higher/lower vertical stratification but mostly on the fortnightly variations of cooscillation of the astronomical tide. Further studies about the diffusion and advection terms in the turbulent processes of the estuary must definitively confirm the occurrence of lateral heterogeneous mixing phenomena between the margins.

- The study area is inserted into the mixing zone of Pará river estuary (about 60 km from the mouth). The results indicated that the distortion and positive asymmetry of the tidal wave in this region suggest that the area of tidal attenuation in the estuary can reach more than 400 km upstream. This manuscript identified lateral variability in water level, which interferes with the hydrodynamic patterns and transport processes, with the entry of tidal wave along the right margin of the estuary.

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