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OCEANOGRAPHIC CHARACTERISTICS OF CAMAMU BAY (14°S, BRAZIL) DURING DRY AND WET CONDITIONS

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ABSTRACT. The Camamu bay (BCM), located at central coast of Bahia, is a pristine region which has been the target of oil and gas activities that could put in jeopardy the whole ecosystem in the case of an oil spill. The present study provides a first overview of its oceanographic characteristics based on a comprehensive set of *in situ* data, which points to a significant temporal variability in the hydrology, a strong marine influence in the dry period and a pronounced runoff signature in the wet season. Depending on the combined effect of the freshwater input and tidal circulation, the main channels of BCM present distinct dynamics. The Maraú channel, in the southern section of the bay, behaves mainly as a partially mixed system, but with spatial variability of the mixing condition. Serinhaém channel, in the northern section of the bay, is well mixed during spring tides and partially mixed during neap tides. The bay mouth is well mixed throughout, both during spring and neap tides. The depuration capability of the bay is seasonally controlled, presenting 90 days and 30 days flushing times for the dry and wet season, respectively.

Keywords: spatial-temporal variability, hydrological cycle, extreme events.

RESUMO. A baía de Camamu (BCM), localizada na porção central do litoral baiano, é uma região considerada intocada que vem sendo alvo de atividades de exploração de óleo e gás, que podem pôr em risco todo o seu ecossistema no caso de um derrame de óleo. O presente estudo apresenta uma primeira visão acerca de suas características oceanográficas, tendo como base um conjunto abrangente de dados *in situ*, que apontam para uma intensa variabilidade temporal na hidrologia, uma forte influência marinha durante o período seco e uma pronunciada assinatura do escoamento superficial durante o período chuvoso. Dependendo do efeito combinado da descarga de água doce e da circulação da maré, os principais canais da BCM apresentam dinâmica distintas. O canal de Maraú, na seção sul da baía, comporta-se principalmente como um sistema parcialmente misturado, mas com variabilidade espacial da condição de mistura. O canal de Serinhaém, na seção norte da baía, apresenta-se bem misturado durante as marés de sizígia e parcialmente misturado durante as marés de quadratura. A entrada da baía apresenta-se bem misturada em toda a sua extensão, durante ambas marés de sizígia e quadratura. A capacidade de depuração da baía é controlada sazonalmente, apresentando 90 e 30 dias para a renovação das águas da baía para as estações seca e chuvosa, respectivamente.

Palavras-chave: variabilidades espaço-temporal, ciclo hidrológico, eventos extremos.

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INTRODUCTION

Estuaries and bays are complex systems subject to the interaction of freshwater discharge, tides and winds, which control its spatial and temporal variability, in time scales from hours to months. The combination of these driving forces generates gravitational circulation and turbulent diffusion, which are the main processes controlling the space and time variability of properties such as salt, temperature, suspended particulates. Understanding the estuarine hydrodynamics is thus important for environmental studies, and fishery and water quality management.

The Brazilian coast between 5°S to 33°S has seventeen large estuaries ($>$50 km^2) within which the most important harbors and coastal cities are located. Vertical mixing in some of these estuaries may vary between well mixed and stratified conditions according to the season or position within the estuary, such as Patos Lagoon (Hartman & Schettini, 1991), Paranaguá bay (Mantovanelli et al., 2004) and Guaratuba bay (Marone et al., 2004). Others present a narrower range of vertical salinity gradients, never reaching stratified conditions of the water column, such as Guanabara bay (Kjerfve et al., 1997), Vitória bay (Rigo, 2004), Todos os Santos bay (Cirano & Lessa, 2007), Cananéia estuary (Bergamo, 2000; Bernardes, 2001), Bertioga channel (Bernardes, 2001) and Itamaracá channel (Medeiros & Kjerfve, 2005). With the exception of Itamaracá channel (Medeiros & Kjerfve, 2005), the baroclinic pressure gradient is apparently an important force driving gravitational circulation in all estuaries. In Todos os Santos bay, Santana et al. (2014) show that barotropic (tides) and baroclinic (density field) are equally important for the residual circulation, with the former inducing horizontal stratification and the latter producing vertical shear.

Most of the large Brazilian estuaries are associated with geological rift systems and are thus classified as tectonic estuaries. Three of these estuaries, Baía de Todos os Santos (BTS, 1233 m^2), Baía de Tinharé-Boipeba (BTB, 237 m^2) and Baía de Camamu (BCM, 384 m^2), are located in the same rift system in the Eastern Brazilian Shelf (EBS), between 13°S and 22°S), according to Knoppers et al. (1999). Here, inland semi-arid conditions and small catchment areas generate small river discharges ($\sim$10 m^3 s^{-1}), which in association with mesotidal ranges tend to produce well mixed water columns, as reported for BTS (Cirano & Lessa, 2007). Amongst these three estuaries, only the larger BTS, surrounded by more than 3 million people and impacted by industrial activities for more than 6 decades, has been the focus of hydrographic investigation (Wolgemuth et al., 1981; Lessa et al., 2001; Cirano & Lessa, 2007; Lessa & Dias, 2009). The BCM and BTB, surrounded by scattered villages and few small cities, have their watershed better preserved (Hatje et al., 2008), with mangrove forest covering more than 45% of the total area and artisanal fishery as the main economic activity. These estuaries have become the focus of attention in the last 10 years with the discovery of oil and gas reserves, with six potential drilling sites located in shallow waters a few kilometers from the coast (ANP, 2013). Numerical simulations performed by Amorim (2005) predicted that an oil spill from such oil fields could reach the BCM within one day in the worst-case scenario. However, despite the environmental and economic value of BCM, no information exists on the estuarine hydrodynamics, residence times and basic climatology, which are important factors to asses the impact probability and severity of spills as well as a guide to future researches.

To address this deficiency, this work aims to provide the first description of the physical oceanography of the BCM, summarizing its physical settings and investigating the water circulation in the dry and wet seasons. It also intends to provide initial grounds for comparisons between the BTS and Camamu bays, in order to foster future investigations on the connectivity between the three estuaries and the continental shelf.

REGIONAL SETTINGS

Camamu bay (BCM), located at the central Bahia coastline ($\sim$14°S, Fig. 1a), is a shallow (mean depth of 5 m) and long ($\sim$55 km in the N-S axis) estuarine system, with a total area of $\sim$435 km^2 ($\sim$12% of open water and $\sim$88% of intertidal area). According to Brazilian Navy nautical charts, the bay volume is approximately $2.3 * 10^9$ m^3, divided into four sectors (Fig. 1b):

i) an estuary inlet (Mutá channel) which is 6.6 km wide at the bay mouth, and three major branches;

ii) Serinhaém channel in the north ($\sim$106 km^2 and $\sim$23 km long);

iii) Igrapiúna, Pinaré and Sorojó channels in the central bay ($\sim$158 km^2) and

iv) Maraú channel in the south ($\sim$119.4 km^2 and $\sim$34 km long).

The coastal climate is tropical humid, with a mean annual precipitation of 2570 mm (Fig. 2b). The rainfall regime has a marked seasonality, with higher precipitation (47% of the annual total) occurring between March and July (austral autumn and winter seasons). Mean annual precipitation decreases to the west, being about 27% lower (2020 mm) at Ituberá, 20 km inland (Fig. 2a). This precipitation trend is a characteristic of the Eastern Brazilian Shelf, where a humid coastal fringe contrasts to an arid interior.

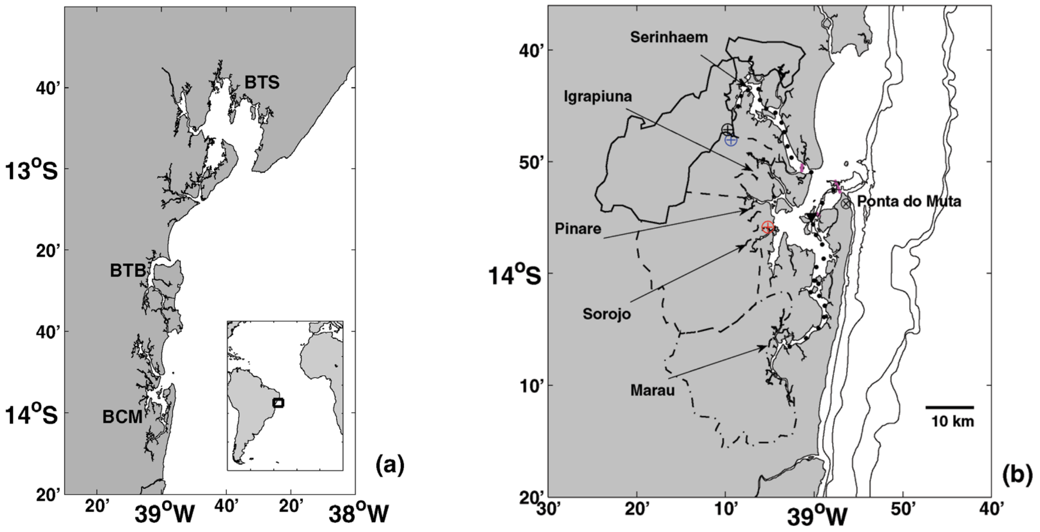

Figure 1 – a) Geographical location of Todos os Santos (BTS), Tinharé-Boipeba and Camamu (BCM) bays along the Eastern Brazilian Shelf. (b) Detail of BCM: The estuary is divided into three sectors. Dots (•) indicate the hydrographic casts; black (⊗) symbol the wind station; triangle (△) tide gauge; red and blue (⊕) symbols the pluviometric stations; black (⊕) symbol the fluviometric station; and purple lines the ADCP transects. The bathymetry is represented by the 10 m, 20 m, 50 m and 200 m isobaths.

The BCM catchment area is approximately 1450 km^2, divided into three sectors: a northern catchment (473 km^2) draining into Serinhaém river, a central catchment (573 km^2) draining into Igrapiúna, Pinaré and Sorojó rivers, and a southern catchment (404 km^2) draining into Maraú river (Fig. 1b). The mean annual discharge at Ituberá stream gauging station is 5.8 m^{3}s^{-1}, with month-mean values varying from a minimum of 5.1 m^{3}s^{-1} in January to a maximum of 6.9 m^{3}s^{-1} in July (Fig. 2c). The mean discharge in the wet (March to July) and dry (August to February) seasons are 6.0 m^{3}s^{-1} and 5.6 m^{3}s^{-1}, respectively. These values represent the flow during 35% and 43% of the time in the dry and wet periods, respectively, and did not show a marked seasonality. The mean maximum daily discharge (Fig. 2c) oscillated from 8.6 m^{3}s^{-1} in May (wet period) to 12.3 m^{3}s^{-1} in December (dry period), suggesting relevant impacts of short-term precipitation events. The mean discharge into BCM was estimated to be 51 m^{3}s^{-1} for the dry period and 55.7 m^{3}s^{-1} for the wet period.

The regional wind field, based on the results of 32-years (1972-2004) of global wind model reanalysis (NCEP, 2013), shows that the wind blows preferentially from the east during the dry period, with mean intensity of 2.7 m s^{-1} near the coast and 4.0 m s^{-1} offshore. During the wet season the wind blows from the southeast with a mean intensity of 2.3 m s^{-1} near the coast and 3.5 m s^{-1} offshore. The southeast shift of wind direction in the winter is ascribed to the southward drift of the South Atlantic high pressure cell, as well as to the more frequent arrival of transient cyclonic systems (cold fronts) that reach latitudes below 10° S (Dominguez, 2006).

METHODS

To achieve a comprehensive survey of BCM, we used available data and conducted oceanographic campaigns during neap and spring tides along dry (21st to 29th September 2004) and wet (20th to 29th July 2005) periods, covering twelve semi-diurnal tidal cycles. The data set was obtained as follows.

Sea level and wind measurements

Sea level oscillations were recorded at the entrance of Maraú channel with a pressure sensor (Fig. 1b) during three distinct time periods not concurrent with the hydrographic surveys: i) in the dry season between December 2002 and February 2003; ii) in the wet season between May 2003 and June 2003; and iii) year-long observations between December 2004 and January 2006.

The local wind speed and direction was measured at Ponta do Mutá (Fig. 1b) simultaneously with the sea level, using a *Wind Sentry RM Young* anemograph. The anemograph stood 18 m above ground and was set to read at 10 Hz and record 15-minute averages. The data was post-processed to fit a standard 10 m wind-level height.

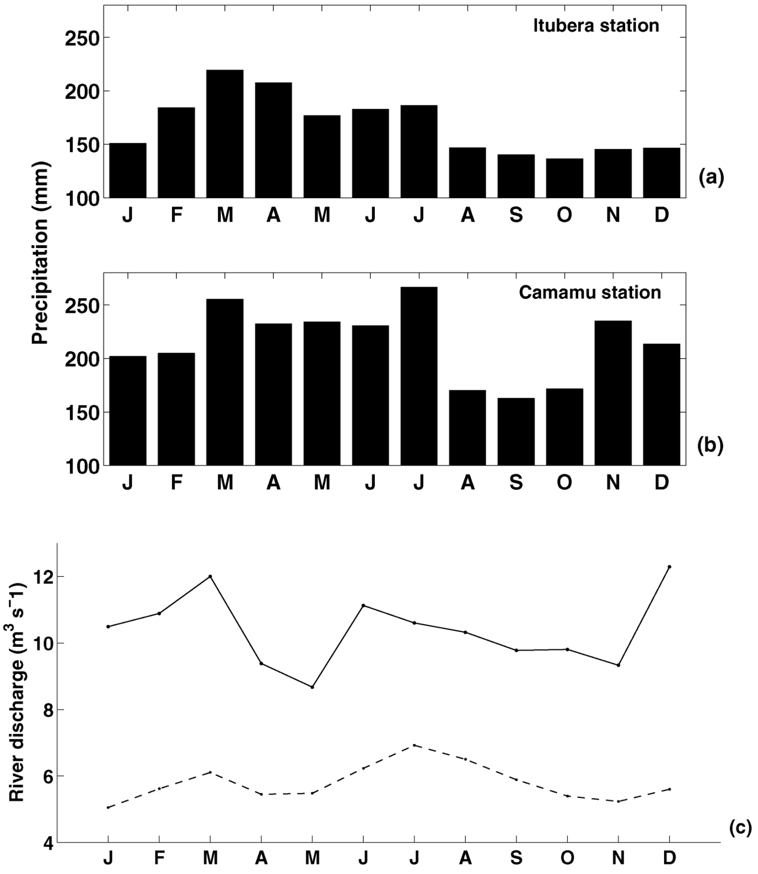

Figure 2 – Month-mean precipitation based on daily time-series from both (a) Ituberá and (b) Camamu pluviometric stations. (c) Month-mean river discharge (dashed line), along with mean maximum daily discharge (solid line) at the Ituberá stream gauging station. See Figure 1 for location.

Low frequency sea level and wind oscillations were calculated by applying a low-pass filter to the raw data (after Walters & Heston, 1982), with a cut-off period of 73 hours for sea level and 50 hour (local inertial period) for the wind time-series.

Rainfall and freshwater data

Daily rainfall was recorded by two stations maintained by the Agência Nacional de Águas (ANA – Brazilian National Water Agency), located at the cities of Camamu and Ituberá (Fig. 1). These time-series are respectively 24 and 40 years long. A station maintained by the Agência Nacional de Energia Elétrica (ANEEL – Brazilian National Eletric Energy Agency) at the mouth of Cachoeira Grande river, the main tributary of the Serinhaém river, gauged the daily-average discharge of 310 km^2 of catchment area which represents 65% of the northern drainage. The data spans 33-year record. Due to the lack of complimentary data sources, the Ituberá station was taken as a proxy for the riverine discharge into the BCM, based on the methodology of flow estimation (not shown) which considers the soil composition of each catchment area and punctual flow measurements distributed at its main tributaries. Although the estimates are conservative, the values found establish a first reference for the freshwater inflow into the BCM.

Hydrographic measurements

Water temperature, salinity and turbidity were measured with a *SBE 19 plus seabird* CTD profiler at a frequency of 4 Hz. The CTD casts were hourly sampled over a complete semi-diurnal tidal cycle (13 hours), concurrent with the velocity measurements, at pre-determined stations symmetrically located with respect to the main channels axis. The casts were averaged at fixed stratum of non-dimensional depth (Miranda et al., 2002) to avoid distortions due to stretch and contraction of the water column during a complete tidal cycle.

Five longitudinal hydrographic profiles were conducted with a second *seabird* CTD profiler along the main axis of the Maraú and Serinhaém channels (Fig. 1b). These measurements were also concurrent with the velocity surveys and were performed following the progression of the high- and low-water slack up channel in the following conditions: i) spring high-water slack in the dry (Serinhaém) and wet (Maraú) seasons, ii) spring low-water slack in the wet season (Serinhaém) and iii) neap low-water slack in the dry (Maraú) and wet (Serinhaém) seasons.

Turbidity readings were converted into concentration of suspended particulate matter (SPM) with best-fit equation determined from ten triplicates of surface and bottom water samples collected along the Serinhaém river channel (not shown). All regressions were significant at the 95% confidence level, with correlation coefficients (R^2) of 0.9 and 0.84 being obtained for the dry and wet periods, respectively.

Velocity structure

The velocity structure were measured along cross-channel transects at Ponta do Mutá and at the entrance of Maraú and Serinhaém channels (Fig. 1b), with a *Workhorse* 600 kHz bottom-track ADCP set to a vertical resolution of 1 m. The along channel velocity structure were hourly measured at each cross-channel transect covering a complete semi-diurnal tidal cycle (13 hours), during both spring and neap tides. The residual structure of along channel velocity were evaluated based on these measurements. In addition, the velocity structure along depth at pre-determined stations located at the cross-channel transects were selected in order to evaluate the velocity variability along a complete tidal cycle.

RESULTS AND DISCUSSION

Sea level variability: tidal and wind induced

Harmonic analysis (after Pawlowicz et al., 2002) of the year-long sea level record at BCM resulted in 67 tide components that accounted for 98% of the sea level variance. The tides into the bay presents a semi-diurnal modulation

$$(F_n = K_1 + O_1/M_2 + S_2 = 0.10)$$

and the tide range varies between a minimum of 0.55 m at neap tides and a maximum of 2.66 m at spring tides.

Tide oscillations tend to be symmetric with 2% difference between the rising-tide/falling-tide times. However, the ratio of the rising-tide/falling-tide times decreased from neap to spring tides, indicating a small change in the sense of tidal distortion from ebb- to flood-dominated, according to the definition of Friedrichs & Aubrey (1998). Spectral analysis showed low frequency oscillations with period of 13.4 days, which can be observed at the low-pass filtered (73 h) sea level record in Figure 3c. The range of the subtidal sea level oscillations (0.09 mm-0.19 m) are approximately half of those observed in Caravelas by Teixeira et al. (2013), with 16 days period.

Wind direction during the dry period was preferentially from E-NE, with mean intensity of 1.25 m s^{-1}. An exception was the SE winds observed in late January and early February (Fig. 3a). The wind direction reversed during the wet season (Fig. 3b), being preferentially from S with mean speed 50% higher (1.87 m s^{-1}).

The subtidal sea level variability was in-phase with the sub-inertial alongshore wind component for both dry and wet periods, in agreement with the coastal Ekman dynamics (Fig. 3a,b), with the time-lag for the highest correlation ($R^2 \sim 0.4$) of 23 and 3.4 hours during the dry and wet seasons, respectively. The sub-inertial zonal wind component, on the other hand, was out-of-phase with the intertidal sub-inertial sea level oscillations, with the highest correlation ($R^2 \sim 0.5$) associated with a time-lag of approximately 1 hour both in dry and wet seasons. Teixeira et al. (2013), after analyzing 4 years of sea level and wind records from Caravelas ($\sim$400 km to the south), found a similar level of correlation ($R^2 = 0.57$ with 5 hours lag) between sea level and along-shore winds. The prevailing south winds in the wet season must have also been responsible for the higher mean sea levels in BCM during May 2005, which were about 0.08 m above the lowest level that occurred in September (Fig. 3c).

Rainfall and freshwater discharge

The total-daily rainfall and the mean-daily discharge at Ituberá station during the survey periods are represented in Figure 4. During the dry season survey (September 2004) the month-total precipitation was 54 mm (Fig. 4a), a low value when compared to the 150 mm climatological value for this period (see Regional Settings). The rainfall distribution shows that most of the precipitation in September occurred outside of the sampling period (Fig. 4a), when the daily-maximum precipitation was 20 mm. However, the mean discharge of 4.6 m^3 s^{-1} registered for this survey was closer to the climatological value of 5.8 m^3 s^{-1} (Fig. 4c).

The month-total precipitation of 238 mm during the wet season survey was 28% higher than the climatological wet season mean of 195 mm and most of the precipitation in the month took place during the survey period (Fig. 4b), when an

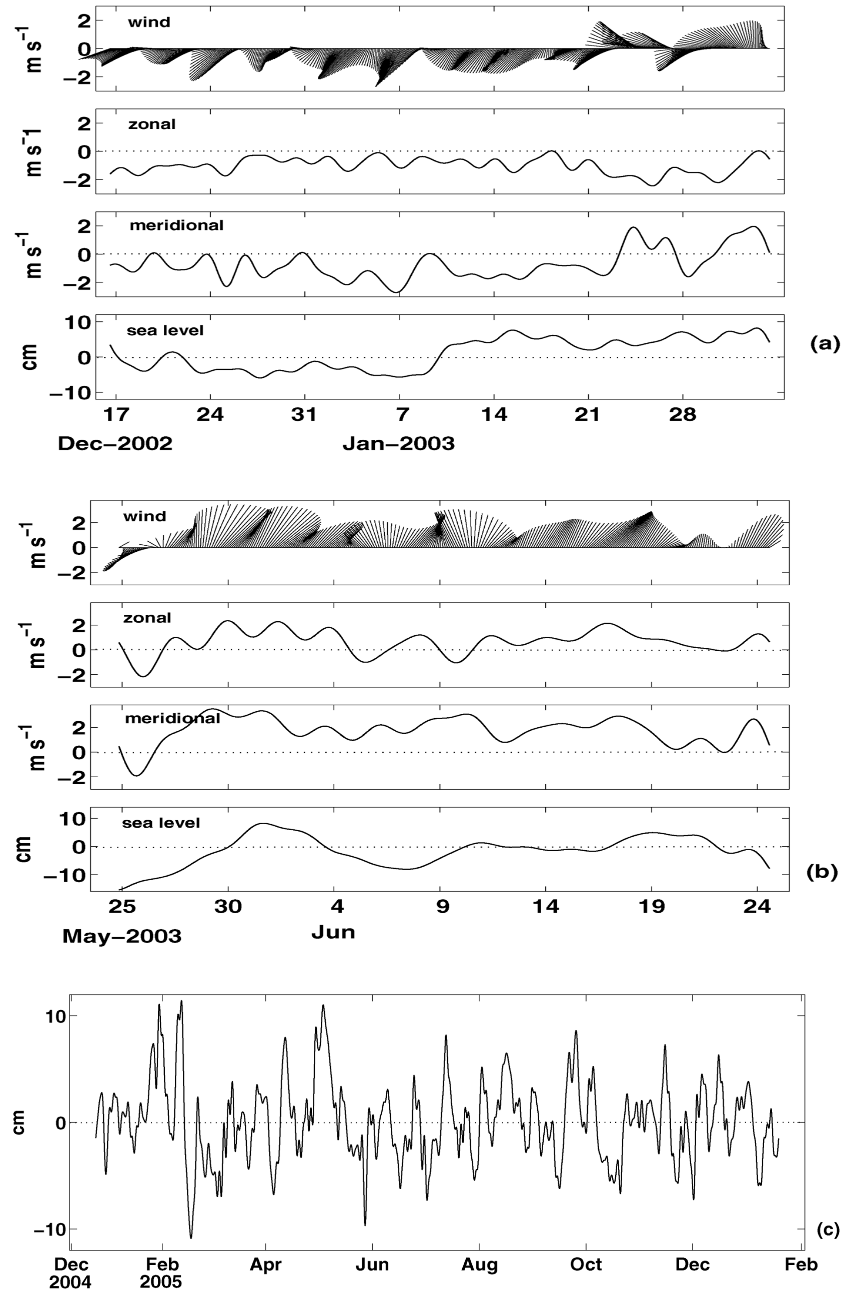

Figure 3 – Sub-inertial wind time-series, zonal and meridional wind components and non-tidal sea level oscillations, during the (a) dry (2002/12-2003/02) and (b) rainy (2003/05-2003/06) periods. (c) The one-year record (2004/12-2006/01) of sub-inertial non-tidal sea level oscillations. Positive wind values are northward and offshore. See Figure 1 for the anemograph and tidal gauge locations.

anomalous high precipitation event (70 mm, ∼30% of the month-total) was registered on the second day of the sampling campaign. The month-mean discharge of 6.7 m^3s^{-1} (Fig. 4d) was similar to the climatological value, however, the extreme precipitation registered during the survey period increased the mean discharge to 9.5 m^3s^{-1}, with a maximum of 10.8 m^3s^{-1} registered on the fourth day of the campaign. Therefore, in seasonal terms, September 2004 survey was performed under typical dry conditions, while the July 2005 survey was performed under extreme wet conditions.

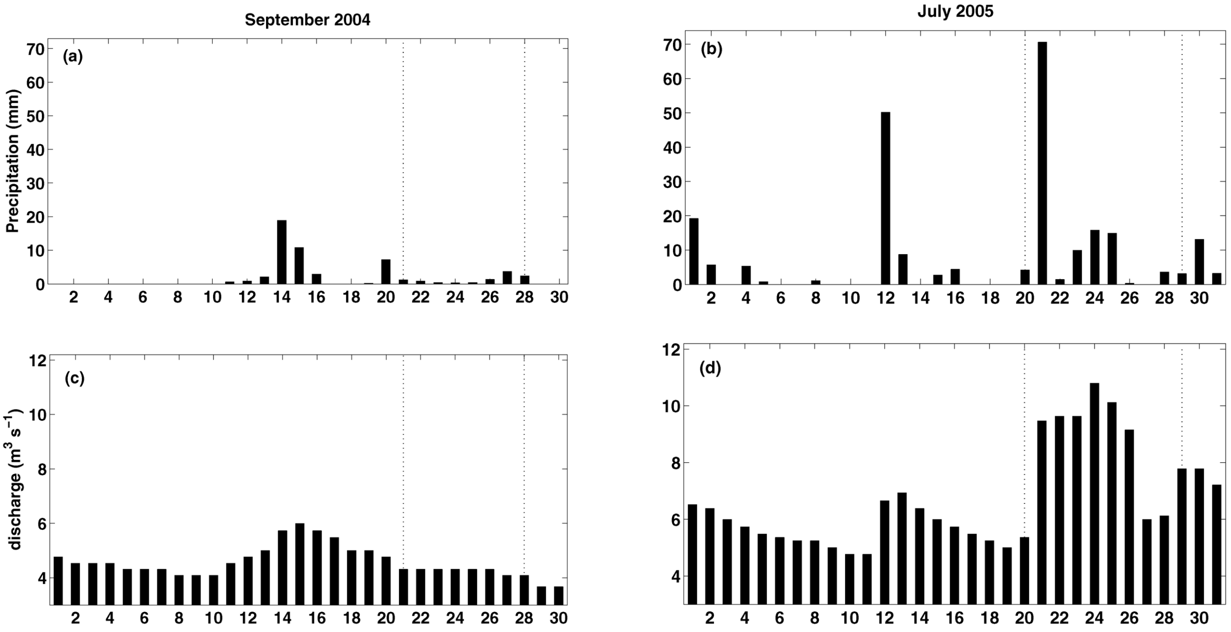

Figure 4 – The daily distribution of (a,b) rainfall and (c,d) stream gauging data at Ituberá station during the months of the survey campaigns. The vertical dotted lines delimit the sampling periods.

Hydrography and flow patterns

Serinhaém channel at the northern branch o BCM, is saltier than Maraú channel at the southern branch. The salinity field measured in Serinhaém channel (Fig. 5a,b) shows maximum value of 32 psu at the estuary mouth and a minimum value of 3 psu at the estuary head (25 km inland). Both minimum and maximum values are likely to be close of the extreme values, given the coincidence of the spring low tide conditions in the wet season (conductive to freshening) and the spring high tide condition in the dry season (that favors salt intrusion). The highest longitudinal salinity gradient, measured at a neap low tide in the wet season (not shown), was about 1 psu km^{-1}. The water column along Serinhaém channel does, however, become partially mixed throughout neap tides (not shown), when surface-to-bottom salinity differences can reach 7 psu (25-32), with vertical gradients of 0.35 psu m^{-1}.

The salinity was measured along the first 37 km at the Maraú channel, or about 80% of its total length. Consequently, the innermost casting station was much farther away from the head of the estuary than its northern branch counterpart. Salinities above 30 psu persisted in the initial 20 km of the channel, both in spring (wet season) and neap (dry season) tides (not shown). The minimum and maximum salinity values in Maraú channel were measured in the spring high tide of the wet season, reaching 22 psu and 36 psu, respectively, when longitudinal gradients achieved 0.4 psu km^{-1}. This is approximately half of the longitudinal gradient measured at Serinhaém channel. The water column was well mixed in both occasions, mostly with vertical salinity gradients in the order of 6*10^{-2} psu m^{-1}. A local exception occurred at km 10 in the wet season, where the gradient was 0.5 psu m^{-1}.

The temperature was nearly homogeneous throughout both Maraú and Serinhaém channels, varying from a minimum of 24.7°C (wet season) to 27°C (dry season) in the Maraú channel (not shown), and from 23.5°C (wet season) to 27.2°C (dry season) in the Serinhaém channel (Fig. 5c,d). Shallower depths limited tidal excursion (discussed below) and a longer residence time warmed up the water during the dry season at the head of the channels, where vertical mean temperatures were up to 0.6°C higher. A similar situation was observed in BTS, where temperatures can be more than 2°C warmer in the far end of the bay (Cirano & Lessa, 2007). A slight vertical stratification (0.6°C) was observed in the deepest sections of the channels during the dry season.

Higher SPM concentrations occurred closer to the bay mouth, reaching maximum values of 30 mg l^{-1} in Serinhaém (Fig. 5e,f) and 20 mg l^{-1} in Maraú (not shown), both in the wet season. Average SPM concentrations in BCM during spring and neap tides were similar to the mean neap tide concentration of 6 mg l^{-1} observed in BTS, as a result of 25 monthly longitudinal profiles executed between 2012 and 2013.

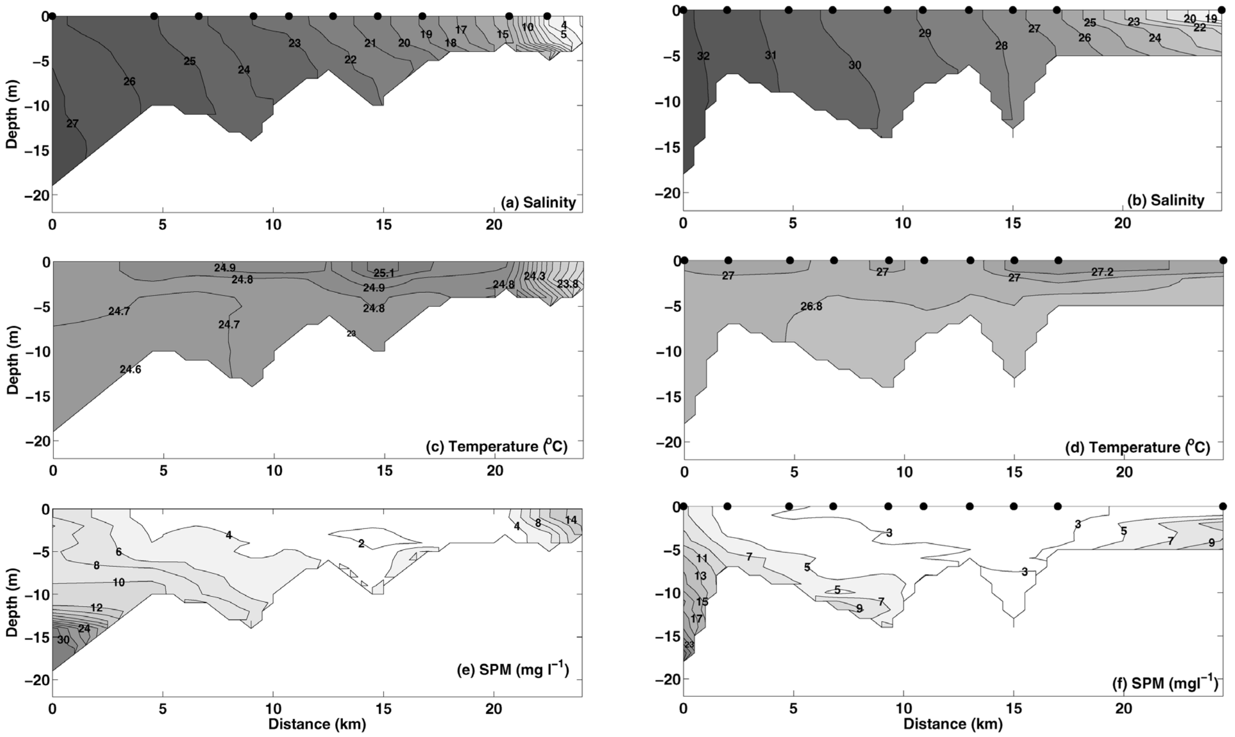

Figure 5 – Along-channel vertical distribution of (a,b) salinity, (c,d) temperature and (e,f) suspended particulate matter (SPM) along the Serinhaém channel in a spring low tide during the wet season (left) and a spring high tide during the dry season (right) of 2004. Distances (km) are in relation to the estuary mouth. Dots represent the position of CTD casts (see Fig. 1 for location).

The temporal variation of the longitudinal current velocity and salinity fields measured in Ponta do Mutá, Maraú and Serinhaém cross-sections (see Fig. 1 for location) are shown for the spring (dry season) and neap (wet season) tidal conditions (Fig. 6). Slack water coincides with low- and high-tide (standing wave oscillation), but peak ebb currents occur 2 hours after high tide, especially in the spring tides. This is a characteristic effect of the tidal distortion observed in the estuary, and has also been observed in the BTS. Maximum current velocities of 1 m s^{-1} was ebb-oriented, with exceptions during spring tides in Maraú channel (Fig. 6c) and neap tides in Ponta do Mutá channel (Fig. 6b), when maximum current velocities were equal in both directions. Ebb dominance was greater in Maraú channel in the wet season spring tide (not shown), when maximum ebb currents (1.2 m s^{-1}) exceeded maximum flood currents (0.8 m s^{-1}) by 50%.

As expected, maximum and minimum salinities coincide with high and low waters, respectively. The water column was well mixed throughout the spring tidal cycles, but became partially stratified during neap tides, mainly in Maraú and Serinhaém channels (Fig. 6d,f) where surface-to-bottom salinity differences were higher than 3 psu. This pattern of water column stratification is similar to that observed in BTS, where surface-to-bottom salinity differences in the neap tide can be higher than 2 psu.

The mean ebb flow ranged from 0.26 m s^{-1} to 0.38 m s^{-1} during neap tides and from 0.78 m s^{-1} to 0.83 m s^{-1} during spring tides (Table 1). During the flood tide the mean channel velocity ranged from -0.28 m s^{-1} to -0.32 m s^{-1} during neap tide and from -0.51 m s^{-1} to -0.72 m s^{-1} during spring tide. The highest mean discharge was 26,631 m^3 s^{-1} for the spring ebb-tide at Ponta do Mutá channel, whereas the smallest discharge was 4,091 m^3 s^{-1} during a neap-flood tide at Maraú channel.

Mean food-tidal currents in Mutá channel was about 0.6 m s^{-1} in the spring and 0.3 m s^{-1} in th neap tidal cycle, thus indicating an approximate tidal excursion of 13 km and 6.5 km in the respective spring and neap tidal cycles. A water parcel entering the Mutá channel t the beginning of a spring-flood tide is likely to reach Maraú inlet. For oil spilled in shelf, and transported to the vicinities of the bay inlet, there is thus a great chance that flooding tides transport the oil up the bay for several kilometers. The amount of time the oil would be held inside the bay will depend on the flushing ability of the bay, discussed in the next section.

The residual flow structures varied between spring and neap

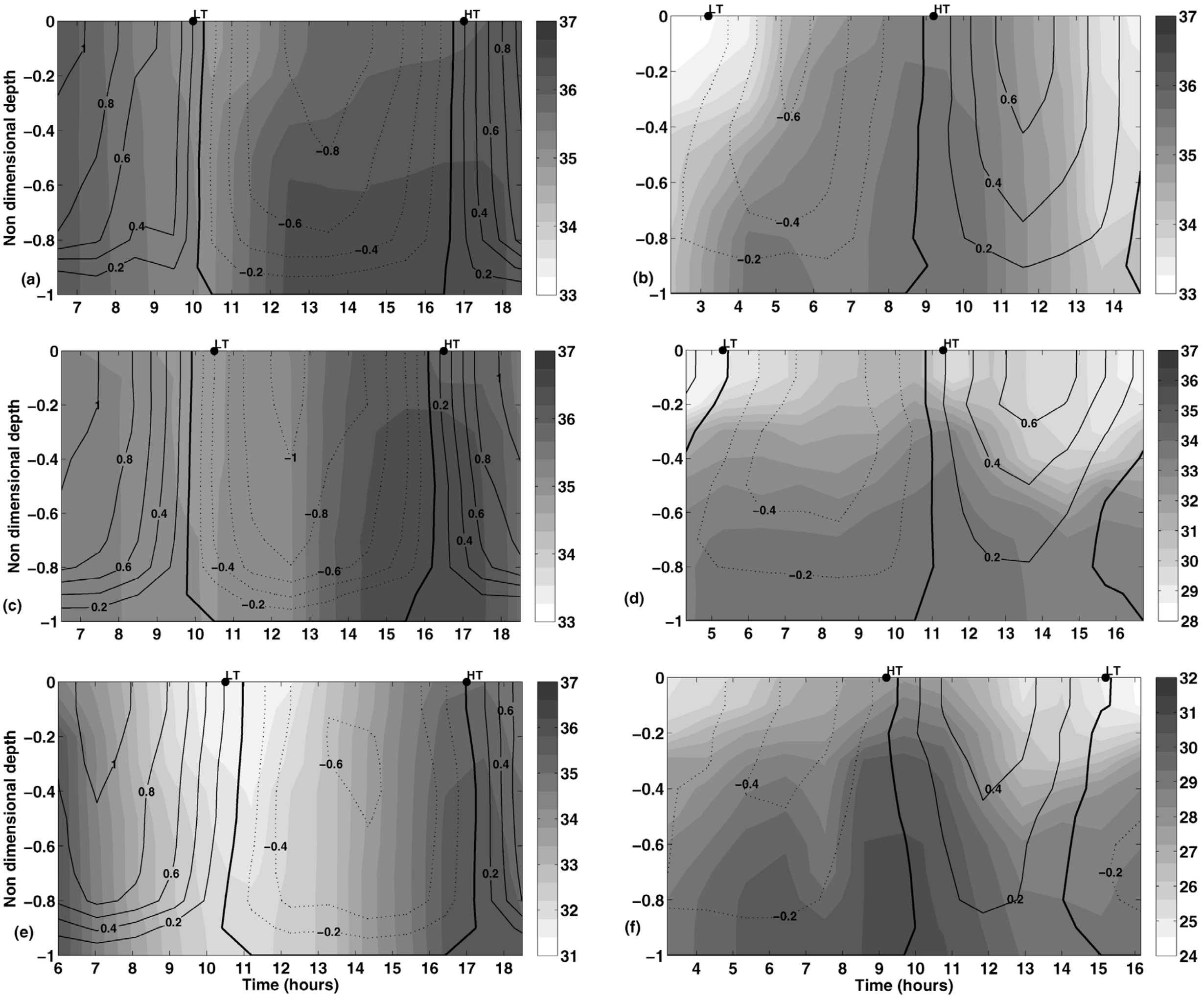

Figure 6 – The hourly vertical velocity (isolines) and salinity structure (shaded area) during dry season spring tide (left) and wet season neap tide (right) surveys, at (a,b) Mutá, (c,d) Maraú and (e,f) Serinhaém channels. Positive (negative) velocities (m s^{-1}) indicate an ebb (flood) flow. HT and LT represent the times of the high and low tides, respectively.

Table 1 – Mean cross-channel velocities and transports in Mutá, Maraú and Serinhaém channels during the dry period under neap (N) and spring (S) tides. U_F, U_E, T_F, T_E and T_R represent the mean velocity (U) and transport (T) during flood (F) and ebb (E) times and the residual (R) values.

Transverse Transects		U_F (m s^{-1})	U_E (m s^{-1})	T_F (m^3 s^{-1})	T_E (m^3 s^{-1})	T_R (m^3 s^{-1})
Ponta do Mutá	N	–0.28	0.26	–9,352	8,867	–90
	S	–0.68	0.83	–22,024	26,631	–977
Maraú river	N	–0.32	0.38	–4,091	4,915	502
	S	–0.72	0.80	–9,255	10,135	–221
Serinhaém river	N	–0.32	0.35	–4,455	4,492	35
	S	–0.51	0.78	–7,279	10,225	329

tides, with horizontal stratifications being more common in the former and vertical stratifications usually observed in the latter. Figure 7 shows the residual flow structure for neap and spring tides in the wet season at Ponta do Mutá, Maraú and Serinhaém channels. Maximum residual currents are 0.06 m s^{-1} in Mutá channel and approximately 0.03 m s^{-1} in both Maraú and Serinhaém channels. Horizontal shear zones are developed in Mutá channel both in spring (more conspicuous) and neap tides (Fig. 7a,b), with a landward residual flow occurring at the center of the channel and seaward residual flow taking place at the margins. This same flow pattern is also observed at the mouth of BTS, except during the wet season, and is ascribed to be influenced by the wind shear. Horizontal stratification was also characteristics of the spring tides in Maraú and Serinhaém channels (Fig. 7d,f), although a tendency for vertical stratification can also be observed, especially in Maraú channel. Vertical stratification developed during neap tides, when tidal mixing is minimum and tidal straining become important (Fig. 7c,e). Seaward flows were well established in the upper 5 m of Maraú channel and in the upper 3 m of Serinhaém channel.

Based on the mean hydrographic and velocity fields monitored in spring and neap tides of both wet and dry periods, the Hansen & Rattray (1966) stratification and circulation diagrams (Fig. 8) indicate that BCM presents a spatially variable classification. Serinhaém channel (Fig. 8a) can be classified as a partially mixed (Type 2) in most of the wet season surveys (blue symbols) and well mixed (Type 1) in the dry season surveys (red symbols). Exceptions to this behavior are ascribed to bathymetric differences in the channel cross-section and the effectiveness of turbulence in promoting mixture.

Maraú channel (Fig. 8b) is vertically homogeneous during spring tides and partially mixed during neap tides. An exception to this pattern was the partially mixed conditions found on the left side of the channel (CTD cast 1, blue crossed circle) during the wet season survey. Maraú channel is better mixed than Serinhaém, as most of the survey lie closer to the lower left corner of the diagram (towards Type 1). The Mutá channel (Fig. 8c) is also vertically homogeneous and even better mixed than Maraú, as the points lie even closer to Type 1a estuaries.

The diagrams indicate that advective transport, associated with gravitational circulation (v→0), of dissolved and particulate matter in Serinhaém and Maraú channels is realtively more important than at Mutá channel. In other words, while turbulent diffusion of the tidal flow dominated transport in all investigated tidal cycles at the bay inlet (v→1), a contribution of the advective gravitational circulation to transport was observed in the wet season in the inner channels. The existence of gravitattional circulation is important for the flushing ability of the bay. The importance of the baroclinic circulation in significantly shortening the residence time has been demonstrated by Liu et al. (2008) and Meyers & Luther (1999).

Flushing Time

Larger longitudinal salinity gradients at BCM imply in smaller flushing times (Tf), which is defined as a bulk parameter for the general exchange capacity of an estuary (Monsen et al., 2002). It can be assessed through the freshwater fraction method $T_{f1} = V(S_o - S){S_o}^{-1}/R$, or through the tidal prism method $T_{f2} = VT/R_{T/2}P$, where V is the subtidal estuary volume (2.3*10^9 m^3), S_o is the ocean salinity, S is the average estuarine salinity, R is the river flow, T is the tidal cycle (12.4 hours), $R_{T/2}$ is the cumulative river discharge over half tidal cycle and P is the tidal prism.

The approximate tidal prisms for BCM, considering the area distribution (infra- and intertidal) and the average spring and neap tidal ranges, are 830*10^6 m^2 and 272*10^6 m^2, respectively. According to Amorim et al. (2012), approximate values for the ocean salinity (S_o) close to the entrance of BCM are 37 in the spring/summer and 36.5 in the autumn/winter. The mean salinity at BCM during dry and wet conditions was assessed through the weighted-average longitudinal salinity distributions for Maraú and Serinhaém rivers, equal to 30.5 and 26, respectively. Salt dilution inside the estuary is related to runoff and atmospheric water discharge during the survey period. The former was approximately 38 m^3 s^{-1} in the dry season survey and 88 m^3 s^{-1} in the wet season survey, whereas the latter (corresponding to the daily mean precipitation times the bay area) were 4.6 m^3 s^{-1} and 139 m^3 s^{-1}, respectively.

T_{f1} considers the time taken by the total freshwater discharge to replenish the freshwater volume existent inside the bay, and resulted in approximately three months for the dry season and one month for the wet season. These values are similar to those calculated by Cirano & Lessa (2007) for the BTS. T_{f2} takes into account how much of the bay volume is exchanged with the ocean during a tidal cycle, as well as how much volume is taken over by freshwater while this exchange is taking place. Because the bay is relatively shallow (2.6 m of average depth), the tidal prism is very effective in turning over the bay volume, and flushing times varies between 1.5 days in the spring to 4.3 days in the neap tides. Considering that T_{f1} is far more conservative than T_{f2}, it should be taken as a reference of the flushing time capability of BCM.

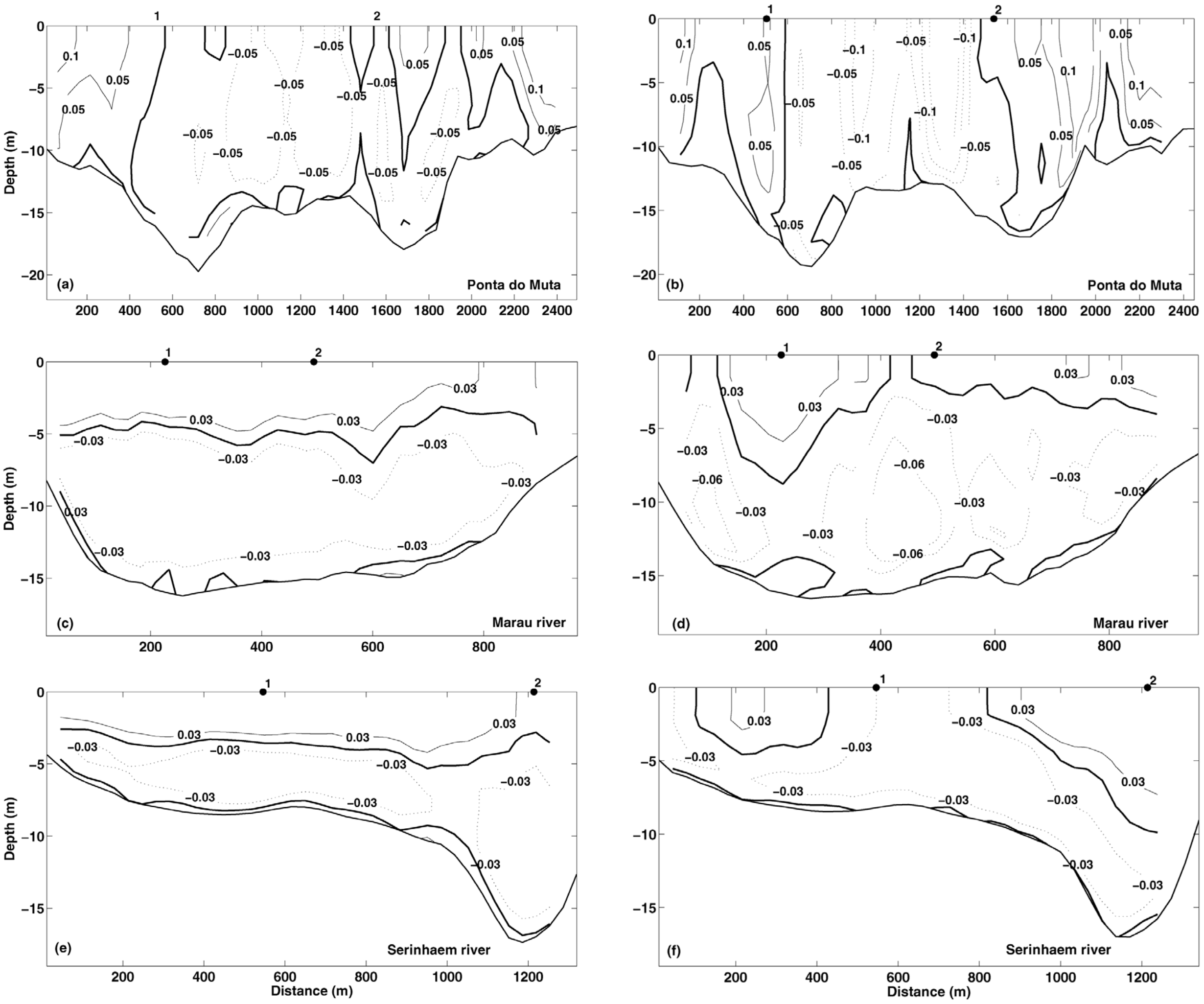

Figure 7 – Residual flow (m s^{-1}) structure in the cross-channel transects at (a,b) Mutá, (c,d) Maraú and (e,f) Serinhaém, during the rainy period survey neap (left) and spring (right) tides. Distances are from the left margin in a continent-ocean orientation. Positive (negative) velocities indicate an ebb (flood) flow. The numbers indicate the position of the CTD casts.

SUMMARY AND CONCLUSION

This work summarizes the results of the first sampling effort to provide information about the structure and variability of the hydrographic properties and currents at Camamu bay (BCM), covering neap and spring tidal cycles during typical dry (September 2004) and extreme wet (July 2005) conditions.

BCM is still considered a pristine region that has been the target of oil and gas exploitation activities in the last 10 years, which could put in jeopardy the whole ecosystem in the case of an oil spillage. The bay presents a semi-diurnal tide modulation ranging between 0.55 m to and 2.66 m during neap and sprig tides, respectively. Tide oscillations into the bay tend to be symmetric, with the difference ratio between the rising-falling tide decreasing from neap to spring tides, indicating a small change in tidal distortion from ebb- to flood-oriented. The intertidal sea level oscillations and remote wind effects are in-phase, in agreement with coastal Ekman dynamics, with the faster adjustment occurring during the wet season when the wind is preferentially from SE. The correlation between the zonal wind and intertidal sea level oscillations is out-of-phase with a quick adjustment ($\sim$1 hour).

The along-system hydrographic structure reflected a strong marine influence during the dry season and a distinct runoff signature prevalent in the wet season, indicating strong seasonal modulation of the hydrography of the bay. The freshwater discharge is spatially heterogeneous, and the Hansen-Rattray classification varies slightly between different bay sectors. Serinhaém

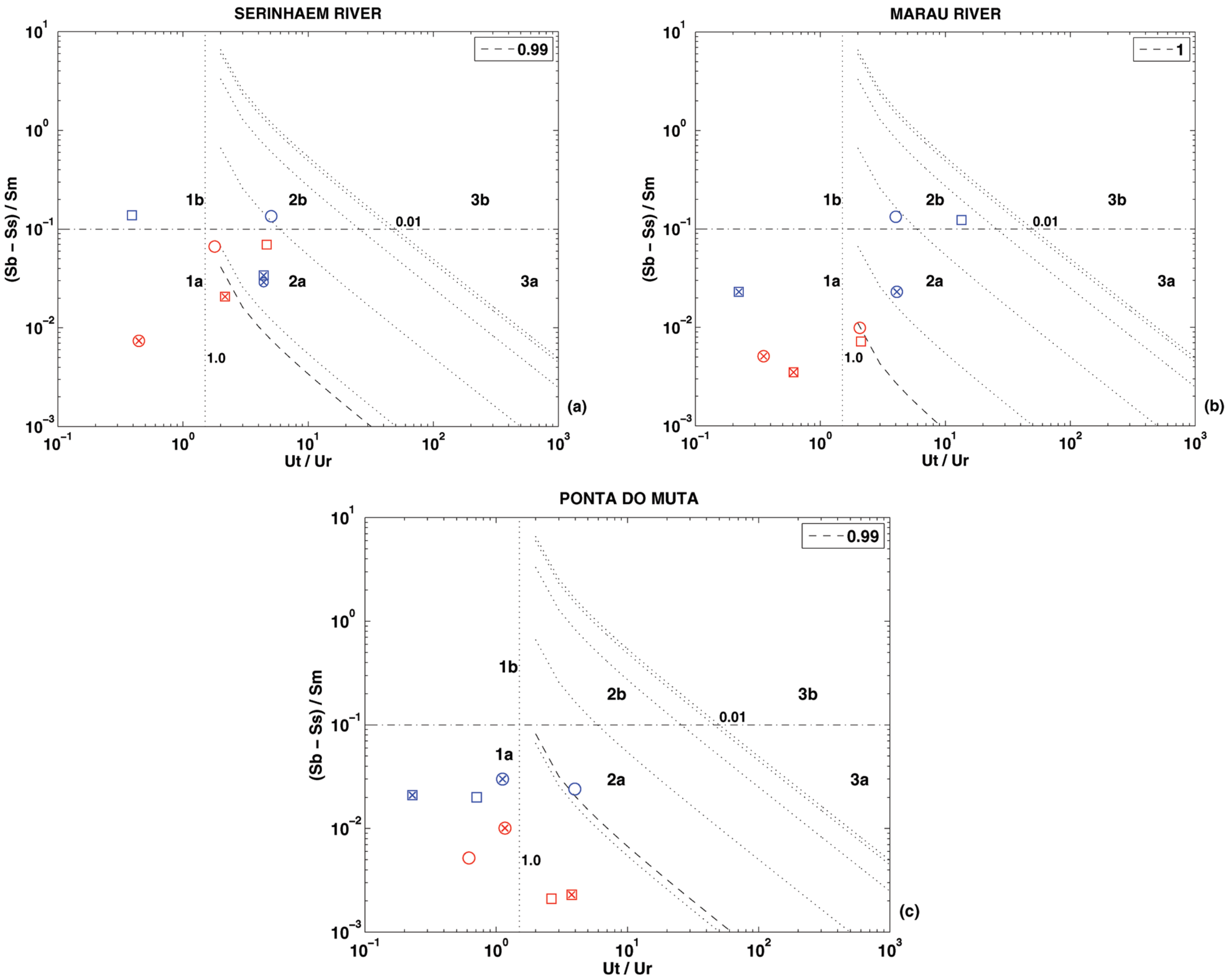

Figure 8 – Stratification-circulation diagram for the (a) Serinhaém, (b) Maraú and (c) Mutá channels. CTD cast 1 (2) is represented as a circle (square); a neap (spring) tide is represented as an empty (crossed) circle (square); dry (rainy) sampling is representing as red (blue) circle (square).

channel behaves mostly as a partially mixed system, whereas Maraú channel is mainly well mixed. Both in Serinhaém and Maraú channels, more vertically homogeneous conditions occur during spring tides, while more partially mixed conditions are prevalent during neap tides. The bay entrance at Ponta do Mutá receives smaller freshwater contribution being more subject to open sea dynamics, presenting well mixed conditions during all tidal conditions in both dry and wet seasons.

The bay system is subject to different depuration capability, depending on the season and tide conditions. Flushing times calculated through the freshwater fraction method were one month and three months for the wet and dry seasons, respectively. These times are in close resemblance to flushing times calculated for BTS, both through analytical and numerical methods. Therefore, spills of contaminated substances inside the bay will be more damaging if it occurs in the dry season than in the wet season. For oil spilled in the continental shelf and transported to the vicinities of the bay inlet, there is a great chance that flood-tidal currents will move it inside the bay as far as 13 km during spring tides. However, its residence time (a different measure from the flushing time of the bay) is impossible to assess given the data available at this point. Based on our results, an effective contingency plan to preserve the ecosystem of the BCM should take into account the seasonality and tide conditions.

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