Thermohaline Properties and Currents of Pisa Sal System, Galinhos/RN, Northeast, Brazil

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Abstract

The Pisa Sal system is a well-mixed tidal channel on the Northern coast of the Rio Grande do Norte state, Brazil, inserted in the Galinhos-Guamaré lagoonar complex. Hourly current and thermohaline measurements during neap and spring tides obtained seasonally in both winter and summer periods yielded information about the physical structure of the system. Tidal currents changes from weakly asymmetric to symmetrical, with higher u-velocities during the ebb-spring tide in the winter period and directions reflecting the channels orientation. From thermohaline and currents properties the system can be classified as a tidal channel forced by semidiurnal mesotide, exhibiting hypersaline (inverse estuary) and vertically well-mixed characteristics, where the turbulent diffusion process seems to be the main responsible for the upstream salt transport. The economical activities of the region (salt industry, shrimp farming and oil industry) associated to the natural phenomena (air temperature, high evaporation level, low precipitation index and tide conditions) are responsible for the environmental impacts in the Pisa Sal system.

Introduction

The Pisa Sal system is located in the Northern coast of the Rio Grande do Norte state, Brazil, between lat. 05° 05'15.6" S and 05°07'52.3" S and long. 36°15"30.0" W and 36°17'39.1" W, exhibiting an area of 19.2 km^2. In the last decade many plants of industry were implanted in the region mainly salt, oil and natural gas processing, shipping and dock activities, and more recently shrimp farm industry. This system has length and mean-wide of 8.0 Km and 150 m, respectively. The mean depth is about 4.3 m. It comprises little dimensions tidel channels (Volta do Sertão, Pisa Salzinho, Labirinto) and two artificially drainaged channels to support a shrimp farm activities. The Pisa Sal system is inserted in the Galinhos-Guamaré lagoonar complex emerged aback a coast-parallel system of old barrier islands having E-W orientation, approximately. In its geological setting, acording to Caldas et al. (2006), the Galinhos-Guamaré lagoonar complex has remained active since the sea reached its actual position for the first time in the Holocene, about 7.000 years BP. During the most of the holocenic marine transgression (~5.900 years BP) transgressive barriers along the coast builded the island-barriers system and propitiated a typical lagoonar sedimentation over the paleo-coast. This changed physiography evolved during lower stands of the sea level due to sedimentary transport along the coast closing the old sea-lagoon channels. As a consequence, dunar transport to West and Southwest was intensified. In 3.600 years BP, approximately, it was built the Pontal de Galinhos, the unique aperture (Galinhos inlet) joining the open sea to lagoon system existing nowadays.

The Pisa Sal system is part of Galinhos-Guamaré lagoon complex and is under influence of a semi-arid climate. Along with lack of fluvial discharge the annual average evaporation (~2,600 mm yr^{1}) is higher than the annual average rainfall (~750 mm yr^{-1}), RADAMBRASIL, (1981). Da Silva *et al.* (2006) have shown that the salinity into the Guamaré and Galinhos estuaries is higher than the adjacent ocean and increases upstream. As a consequence, the associated increasing of the density causes the water to sink and flow out towards the sea near the bottom, resulting in a two layer circulation but with reverse movement. Ocean water enters the estuaries in the upper layer and hypersaline estuary water leaves them in the lower layer, characterizing them as "inverse estuary", Tomczak (2000).

Studies of thermohaline properties and currents of Pisa Sal system are basic to understand the water circulation under seasonal and spatial variability, to classify its main channel and to understand the mechanisms responsible transport of substances. The knowledge how they act on the water quality is fundamental to prevent anthropic environmental impacts in that system.

Materials and Methods

A strictly controlled tidal regime was used for the samplings in order to ensure that a reliable comparison could be made among seasons and sites of the Pisa Sal system. Hourly current and thermohaline measurements, comprising 2 tide cycles (25 hours), during neap and spring tides obtained seasonally in both winter (08 to 09/06/2007 and 15 to 16/06/2007, respectively) and summer (17 to 18/12/2007 and 26 to 27/12/2007, respectively) periods were carried out in the along-channel stations numbered as 1 to 3 (see Figure 1). Vertical profiles of hydrographic properties were made using a Valeport CTD/Current Meter, model MkIII fixed on a boat moored in the respective station position. Measurements were carried out at 1 meter depth intervals from surface to within 0.6 m of the bottom. Collected data were processed using the software ESTUARIO, adapted by Bérgamo (2001). Current velocity vectores $\vec{V}$ were decomposed according to the equations

$$u = V\cos\theta \qquad (1)$$

and

$$v = V sen\theta \qquad (2)$$

where, V is the vector modulus and θ the angle measured counterclockwise relative to the abscisse axis (David e Kjerfve, 1998). Here θ is considered as

$$\theta = 90^0 - (dd \pm D) \pm \gamma \qquad (3)$$

where dd is the velocity direction measured by the instrument relative to the north magnetic, D=-21,65° is local magnetic declination (DHN, 2003) and γ represents an angle that orientates the abscisse axis along with the channel axis on each observation station. (+) indicates rotation in clockwise and (-) counterclockwise sense, respectively.

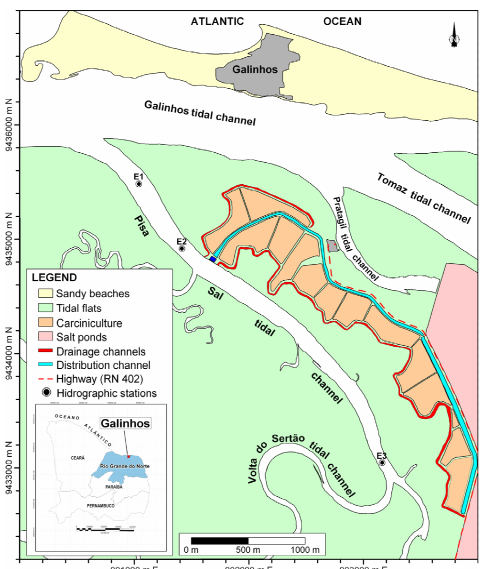

Figure 1: The Pisa Sal system and localization of hydrographic stations.

In this work only the u component is discussed since it is the main determinant for sedimentary transport. Positive or negative values for u indicate outward or inward system, respectively.

Tide current analysis

Winter measurements

Figure 2, a-d, show the time variability of *u(t)* profiles in neap and spring tides. In the analysis it was also neglected the wind influence to the vertical current structure and used the maximum friction condition on the bottom. *u(t)* shows a weakly asymmetric character and little vertical stratification, except in times immediately after neap high or low slack waters. In spring tides *u(t)* is symmetric on E1 station, approximately symmetric on E2 Ebb tide velocities are higher than flood tides along the channel extension.

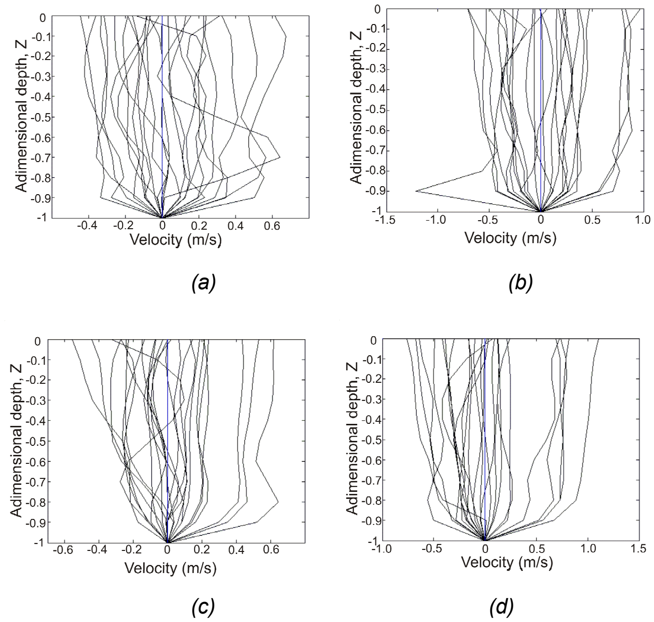

Figure 2: Time variability of *u(t)* profiles in neap and spring tides in winter. *(a)-(b)* on E1 and *(c)-(d)* on E3 station, respectively.

The maximum absolute for *u* occurs in spring tides. These values are (1.11 m/s) on E3 and (1.21 m/s) on E1, respectively. The u vertical profiles for neap and spring tides show *u* values higher on surface than on bottom. A relatively weak stratification is observed with the highest values extending up to the half of the water column during neap as on ebb as on flood tides. On high and low slacks waters there is no current stratification, indicating a constant velocity along the water column.

Numerical integration of *u* with respect to depth was used to evaluate *<u(Z)>*, whereas u_a is the residual velocity calculated from numerical integration of *u* with respect to depth and time. Figure 3, a-d, show *<u(Z)>* and u_a observed in station E1 and E3 in neap and spring tides.

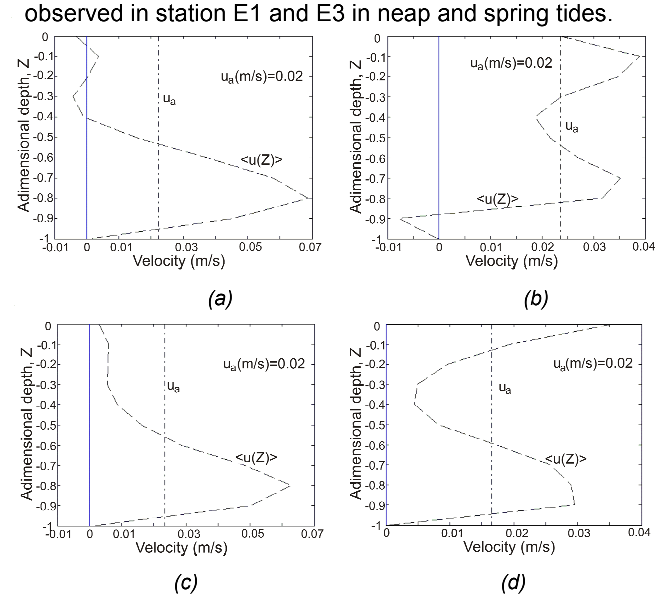

Figure 3: *<u(Z)>* and u_a observed in neap and spring tides in winter. *(a)-b)* on E1 and *(c)-(d)* on E3 station, respectively

The u_a values along channel are equal to 0.02 m/s outward for neap and spring tides on stations E1 and E3. These values are a clear indication of lack of river discharge in the Pisa Sal system.

Summer measurements

Figure 4, a-d, show the time variability of *u(t)* profiles in neap and spring tides.

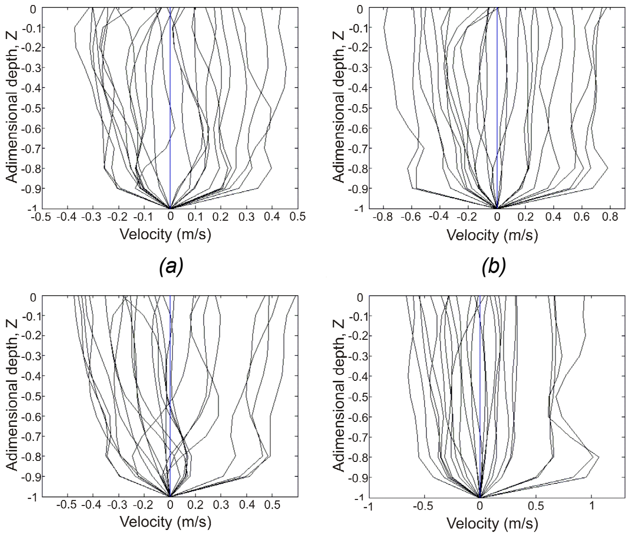

Figure 4: Time variability of *u(t)* profiles in neap and spring tides in summer. *(a)-(b)* on E1 and *(c)-(d)* on E3 station, respectively.

Time variability of *u* in neap tides shows a weak symmetric behavior in the mouth and a strong asymmetric character in the head of the channel. Ebb velocities are higher than flood. The maximum absolute for *u* occurs in spring tides. The observed values are (0.79 m/s) on E1, (1.21 m/s) on E2 and (1.07 m/s) on E3, respectively.

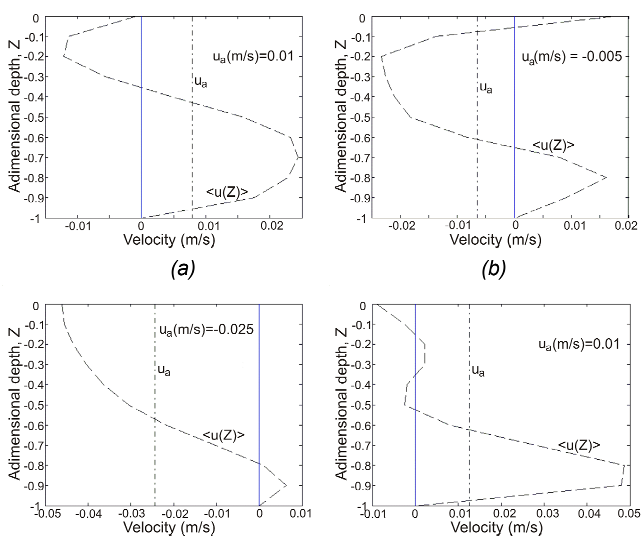

Figure 5: *<u(Z)>* and u_a observed in neap and spring tides in summer. *(a)-b)* on E1 and *(c)-(d)* on E3 station, respectively

Generally, the residual velocity u_a is flood predominant in the mouth and ebb prevailing in the head of the channel. On the middle portion of the channel u_a=0.

Salinity and Temperature Distribuitions

Aiming to classify and to understand the mechanisms responsible by transport of substances measurements of thermohaline properties in the Pisa Sal channel were made under seasonal and spatial variability.

Thermohaline properties in winter

The water mean temperature values change from 26.90 °C in spring to 27.33 °C in neap tides, indicating a tendency for all data observed. The maxima values of temperature were often observed on E3 station. The temperature profiles indicate weak depth stratification in this parameter as an indication of vertical admixture. Several isolated nuclei of high and low temperatures were identified along the Pisa Sal channel.

Results of salinity measurements show minimum and maximum absolute values of 36.41 psu on E1 station and 41.08 psu on E3 station, respectively, whereas the mean values changed from 37.43 psu on E1 to 39.75 psu on E3. This is an indication that the salinity increases from mouth to the head of the system. Figure 6 shows the longitudinal distribution of salinity along the channel.

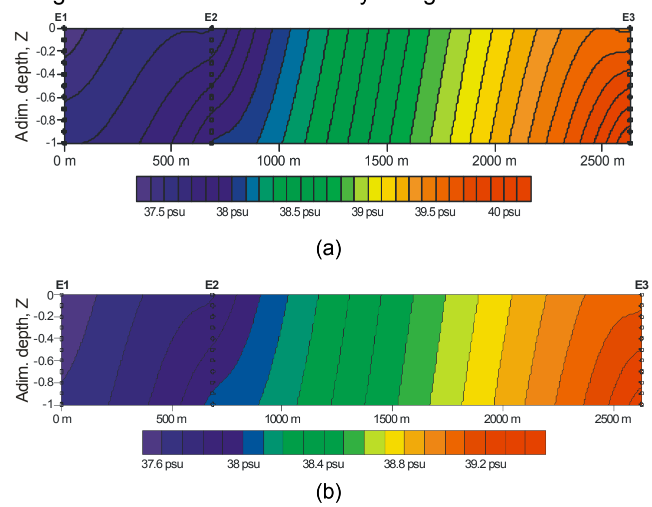

Figure 6: Longitudinal distribution of salinity along the Pisa Sal channel (a) neap and (b) spring tides in winter.

Vertical profiles of salinity have shown weak stratification as in neap as in spring tides. Together with the observed temperature profiles the Pisa Sal channel exhibits a well-mixed estuary behavior. The highest values of salinity were observed near low slack waters. During spring tides salinities are higher on E1 and E2 while during neap tides they are higher in E3.

Mean values of σ_t change form 24.50 on E1 to 26.23 on E3, while minimum and maximum absolute values of 23.52 on E2 and 27.25 on E3, respectively, were observed for σ_t. Following the salinity behavior (see

Figure 5), the density increases inwards as during neap as during spring tides. Its distribution pattern is similar to that of salinity, exhibiting almost vertical isopicnals mainly during spring tides.

Thermohaline properties in summer

Mean temperatures observed changed from 27.01°C on E1 to 29.25°C on E3, therefore, higher than those observed in winter. During neap tides the temperature increases inwards, while remains almost constant along channel during spring tides. A weak vertical stratification was observed near low slack waters on E1 and E3 stations indicating possibly vertical admixture in the system also in this period. Only in spring tides one isolated nucleus of low temperature was also identified near the bottom, observed on E1 in the mouth of the system.

Results of salinity measurements show minimum and maximum absolute values of 37.73 psu on E1 station and 43.18 psu on E3 station, respectively, whereas the mean values changed from 39.01 psu on E1 to 41.90 psu on E3. The salinity increases from mouth to the head of the system during neap and spring tides. Figure 7 shows the longitudinal distribution of salinity along the channel.

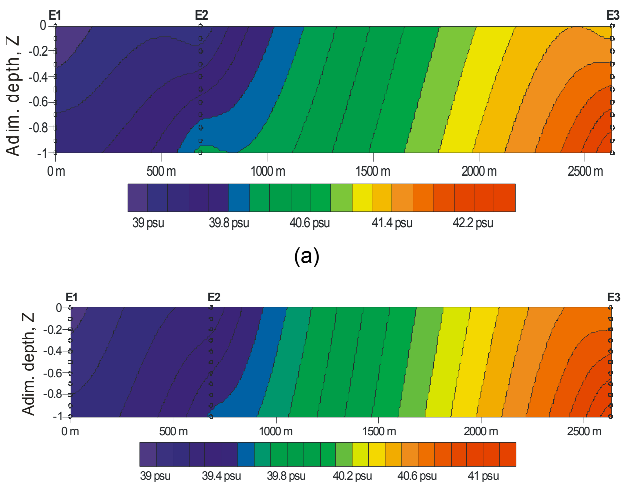

Figure 7: Longitudinal distribution of salinity along the Pisa Sal channel (a) neap and (b) spring tides in summer.

Mean values of σ_t change from 25.47 on E1 to 27.32 on E3, while minimum and maximum absolute values of 23.82 and 28.83 on E3, respectively, were also observed for σ_t.

Despite of high absolute and mean values of temperature, salinity and density observed in summer compared to those in winter, the Pisa Sal system shows similar behavior as seen from their thermohaline properties.

Figure 8 shows the time variability of salinity relative to the tide co-oscillation observed on E1, E2 and E3 stations during winter and summer periods in neap and spring tides.

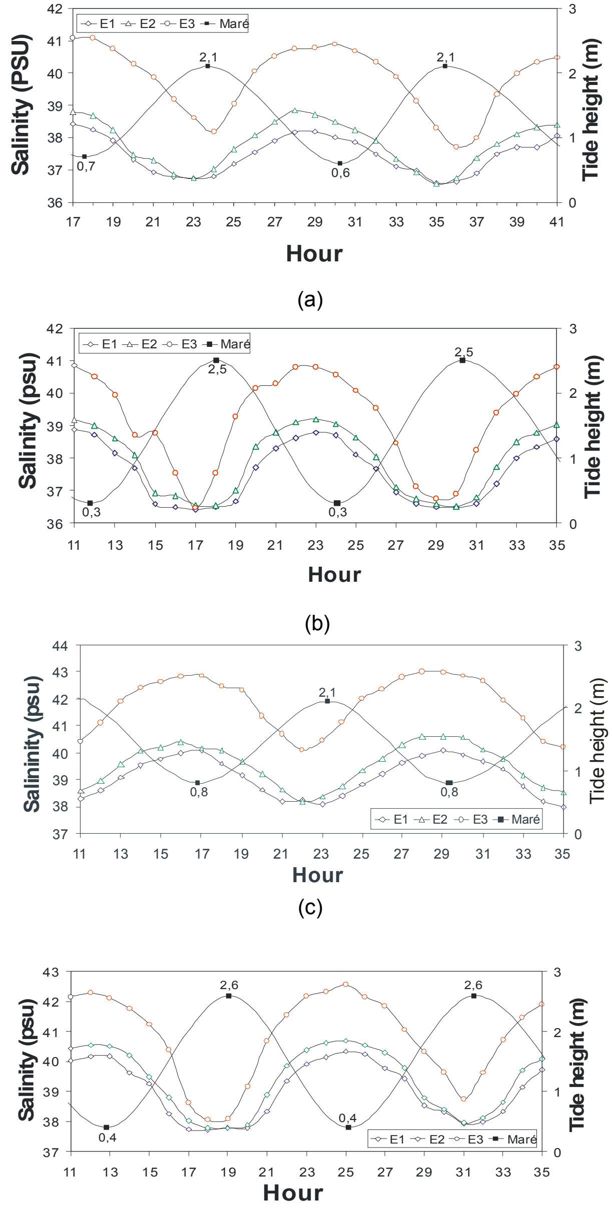

Figura 8: Hourly variability of salinity relative to the tide co-oscillation on E1, E2 and E3 stations in winter and summer during neap and spring tides

As seen in the Figure 8, when sea water penetrates the Pisa Sal channel salinity decreases reaching minima values near high slack waters while the maxima values are attained near low slack waters. In addition, the salinity on E3 is higher than E2 which in turns is higher than E1. This means that the salinity is lower in mouth than in head of the channel and seawater enters into the system to dilute their waters.

Conclusions

The behavior of the longitudinal component of current velocity *u* is relatively symmetric along channel presenting events of weak asymmetry. The ebb currents are higher than flood for all observations while the highest values occur in winter. The *u* directions are along the channel, respectively, NW-NNW for ebb and SE-SSE for flood waters.

The mean value of *u* respect to depth $<u(Z)>$ and the residual velocities u_a in winter indicates predominance on ebb while in summer the predominance depends on the tide be neap or spring. The low u_a values for all observations mean lack of riverine discharge and that the currents in the channel are only tidel forced.

Absolute and mean values of temperature, salinity and density observed in summer are higher compared to those in winter. Moreover, the highest values were found in neap tide. Weak vertical stratifications were observed for temperature but the salinity increases from surface to bottom. On the other hand, the salinity increases from mouth to head of the system in all observations.

On the other hand, the tide co-oscillation seems to be the responsible phenomenon for salt transport in the channel and that seawater penetrates the Pisa Sal system to dilute their waters. The salinity variation due to admixtures regulates the vertical and longitudinal density distribution of the fluid, since the temperature differences are less significant. Therefore, the longitudinal gradient of the density (salinity) generates important density currents due to baroclinic effects which together with tidel currents should dominate the hydrodynamic characteristics of the Pisa Sal system circulation.

In conclusion, high evaporation level, low precipitation index, lack of fluvial contribution, thermohaline and current properties observed in the Pisa Sal system indicated that this marine environment shows hypersaline, inverse circulation and vertically well-mixed characteristics and can be classified as a vertically well-mixed estuary, according to Cameron e Pritchard (1963) criterion. The turbulent diffusion process seems to be the main responsible for the upstream salt transport.

Acknowledgments

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