

ON THE DYNAMICS OF SACO DA MANGUEIRA EMBAYMENT – PATOS LAGOON (BRAZIL)

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INTRODUCTION

The bottom topography of the Patos Lagoon estuary is characterized by large shoal areas (< 3m) and deeper channels (18 m) in the lower estuary. Around 28% of the estuarine area is formed by shallow protected embayments, where the dynamics is restricted (PERSICH *et al.*, 1996).

The Saco da Mangueira embayment is a semi-enclosed system connected to the Patos Lagoon estuary through a narrow entrance (Figure 1). This system is of major importance for communities living around Rio Grande City (south of Brazil), being subject to the influence of multiple and conflicting economical and recreational activities. The Saco da Mangueira embayment receives 29% of the total effluents from Rio Grande City, which includes contributions from domestic, pluvial and industrial (fisheries, fertilizers, oil refinement) effluents, most of which are not treated (BAUMGARTEN *et al.*, 2001). BAUMGARTEN *et al.*, (1995) classified the area as eutrophic, although anoxic conditions are not observed due to the local dynamics.

Little is known, however, about the factors controlling the dynamics of the Saco da Mangueira embayment and the possible effects of the proposed developments on the exchanges between this area and the main Patos Lagoon access channel. PEREIRA (1997) carried out what is probably the only hydrodynamic study of the area. The author applied the finite element model *Shallow* prescribing the astronomic tide at the mouth of the embayment as boundary condition and forcing the system with a constant wind. The domain, however, was limited to the embayment itself, not taking into account the circulation in the Patos Lagoon estuary and its interaction with the adjacent coastal area.

Therefore, the objectives of the present study are: 1) to investigate the mechanisms controlling the dynamics of Saco da Mangueira under the predominant forcing conditions; 2) to evaluate the influence of the estuarine

baroclinic circulation on the dynamics of the area.

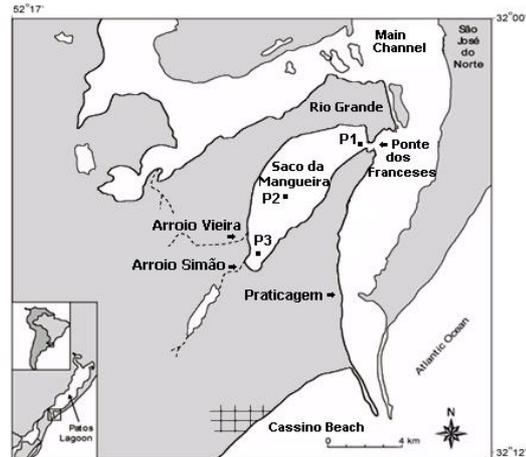


Figure 1 - The Patos Lagoon estuary and Saco da Mangueira embayment. After Baumgarten *et al.* (1998).

DESCRIPTION OF THE AREA

The Saco da Mangueira embayment (Figure 1) is a semi-enclosed shallow system (mean depth of 1 m) which is connected to the Patos Lagoon estuary through a narrow entrance (240 m width). The system is 10 km long and 3.5 km wide, with a superficial area of 27 km², interacting with the Patos Lagoon estuary in one end and receiving little freshwater contribution from Vieira e Simão streams in the other.

The Patos Lagoon estuary (Figure 1) occupies approximately 10% of the area of the lagoon and is characterized by wide shallow areas (80%), natural and artificial navigation channels and shallow embayments. The only connection of this estuary to the South Atlantic

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Ocean is through a narrow entrance (750 m width). The mean and maximum depths in the access channel are 14 and 20 m, respectively.

The estuary is micro-tidal, tides are mixed, mainly of the diurnal type, with mean tidal amplitude of 0.47 m. The dynamics are therefore essentially dependent on the wind acting on the water surface (set-up/set-down mechanism), the wind action in the coastal area (Ekman transport acting 90° to the left of the wind direction), and on the freshwater discharge at the top of the lagoon (FERNANDES *et al.*, 2001; 2002; MÖLLER *et al.*, 2001).

Measurements and numerical experiments carried out by MÖLLER *et al.*, (1996; 2001) and FERNANDES *et al.*, (2001; 2002; 2004) under the predominant wind conditions, showed that when the wind comes from the NE, its local effect decreases the water level in the north of the lagoon and piles up water at Feitoria (Figure 2). The non-local effect driven by the Ekman transport reduces the water level close to the mouth. The combination of these two forcing effects generates a barotropic pressure gradient towards the ocean, which favors flushing of the lagoon water. When the wind comes from the SW, the local effect increases the water level in the north of the lagoon and decreases at Feitoria, and the non-local effect now piles up water close to the mouth. The combination of both effects generates a barotropic pressure gradient towards Feitoria, which favors water penetration into the lagoon.

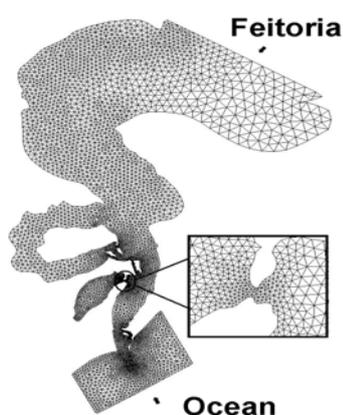


Figure 2 - Finite element mesh used in the simulations.

During periods of intense freshwater discharge ($> 4000 \text{ m}^3 \text{ s}^{-1}$), the SW wind action is limited by the barotropic gradient generated

between the Patos Lagoon and the Ocean. In these events the lagoon can remain fresh and the mixing zone can be restricted to the mouth of the estuary or be transferred to the adjacent coastal area (MÖLLER and CASTAING, 1999), generating a considerable plume (FERNANDES *et al.*, 2002).

METHODS

The Numerical Model

The large spatial and temporal variability of the Patos Lagoon and its estuary suggests that a detailed study of the dynamics of the area can not be carried out based on field data alone. One possible solution is the use of numerical models as powerful tools for interpolating/extrapolating data in the spatial and temporal domains. Results presented by FERNANDES (2001), FERNANDES *et al.*, (2001; 2002; 2004; 2005) highlight the necessity of using bi and three-dimensional numerical models for studying the dynamics of the area.

The TELEMAC model was chosen to carry out two- and three-dimensional hydrodynamic simulations for the lower estuary of the Patos Lagoon. TELEMAC is a finite element flow model developed by the *Laboratoire National d'Hydraulique (EDF, France)* to simulate the flow in estuaries and coastal zones (HERVOUT and VAN HAREN, 1994; 1996).

Model Set Up

The model calibration and validation for the Patos Lagoon was carried out by FERNANDES *et al.* (2001; 2002), SCHILLER (2004), and CECILIO (2004). Results indicate the TELEMAC system as an appropriate tool for studying the dynamics of the Patos Lagoon.

The boundary conditions used in the simulations were established based on data collected between 07/1999 and 08/1999, which represents a typical winter scenario: high freshwater discharge and the passage of strong weather fronts. The open boundaries in the domain were forced with time series of sea surface elevation (SSE) (Figure 3A). The superficial open boundary condition is a stress calculated based on a prescribed time series of wind speed and direction, presented in Figure 3B in the form of velocity vectors.

Thus, time series of SSE, current velocity and salinity were extracted from the modeling results in selected nodes inside the estuarine area, especially inside the Saco da Mangueira embayment. The wind data was decomposed in a longitudinal and transversal component and rotated anti-clockwise by 37° degrees, in order to make the y axis coincident with the main Saco da Mangueira axis (shore parallel). These time series were processed applying techniques in the time domains. Cross-correlation analyses were carried out in order to verify possible phase lags between the series. Statistical tests based on the difference in variances of both time series were applied to evaluate the significance of differences between them.

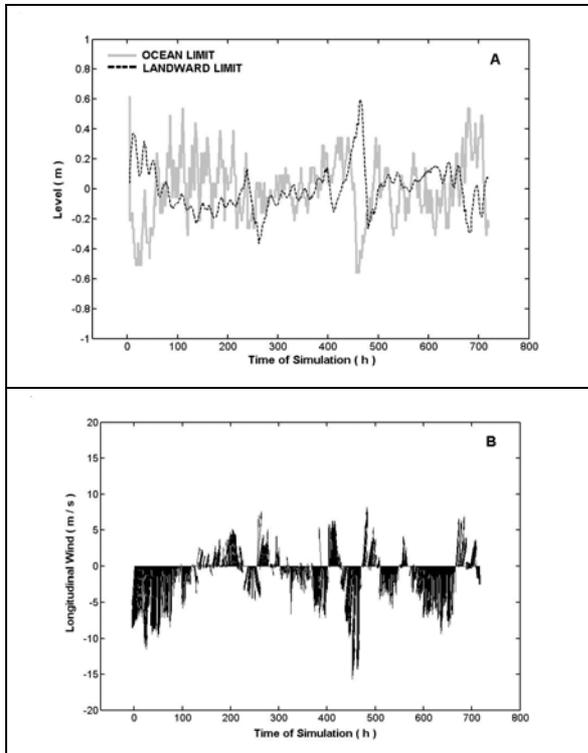


Figure 3 – (A) Time series of SSE prescribed at the ocean and landward limits of the Patos Lagoon estuary. (B) Time series of wind prescribed as the superficial boundary condition.

RESULTS

Assessing the Importance of Three-Dimensional Simulations for the Saco da Mangueira Embayment

An initial approach to evaluate the importance of considering three-dimensional numerical experiments for studying the

dynamics of shallow embayments in the Patos Lagoon estuarine area was to compare results from two- and three-dimensional experiments carried out for the same period and set-up.

Figure 4 presents SSE (Figure 4A) and current (Figure 4B) results from both modules in one point inside Saco da Mangueira embayment. A statistical test was carried out in order to evaluate if the mean difference between the time series is significant. Results from point 2 (Figure 1) indicate that the time series of SSE calculated by the two- and three-dimensional modules can be considered similar ($\alpha=0,05$). Results extracted from point 1 (Figure 1), however, indicate that the mean difference between the time series of current velocity is significant and the series can be considered different ($\alpha=0,05$).

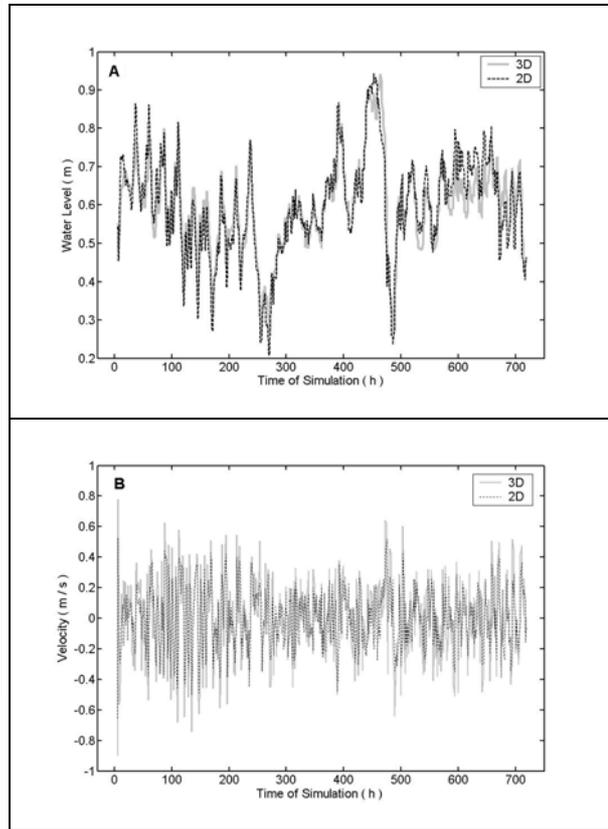


Figure 4 – Comparison between two- and three-dimensional results. (A) SSE from point 2 and (B) current velocity from point 1.

The rate calculated from the mean difference between the two- and three-dimensional current velocity, and mean current velocity from the three-dimensional module indicates the contribution of the 3D simulation

in relation to the 2D results. The resulting value is 47% ($\pm 3\%$), indicating that the two-dimensional model represents only half of the three-dimensional current velocity calculated for that area. Thus, an estimative of the exchange processes between the Saco da Mangueira embayment and the main access channel based on results from two-dimensional simulations is likely to be underestimated.

Figure 5 presents a similar comparison carried out for salinity results from the two- and three-dimensional simulations. Although the two-dimensional module manages to represent the main salinity variations throughout time in point 1 (Figure 5 A), results suggest that salinity is underestimated in comparison with three-dimensional results, reaching a difference of 25 units when $t=700$ h. Results for points 2 and 3 (Figure 5 B and Figure 5 C) suggest a poor representation of the salinity distribution in the inner parts of the embayment when considering the 2D approach, reaching a difference of 10 units when $t=150$ h and $t=700$ h (point 2).

Furthermore, results from the two-dimensional simulation show that the salinity distribution is mainly restricted to the area where the Saco da Mangueira embayment connects to the main access channel (around point 1). This behavior is likely to be related to: 1) a poor representation of the two-dimensional circulation in the main access channel, reducing the advection of salt; 2) the absence of the baroclinic component of the circulation. Taking the baroclinic component of the circulation into account in the model will generate flow in the direction of the density gradient, favoring water to move further and also to the inner parts of the embayment. Thus, results clearly illustrate the necessity of applying the three-dimensional module to properly represent the dynamics of Saco da Mangueira embayment, and suggest that mixing estimates based on a two-dimensional approach are likely to be underestimated.

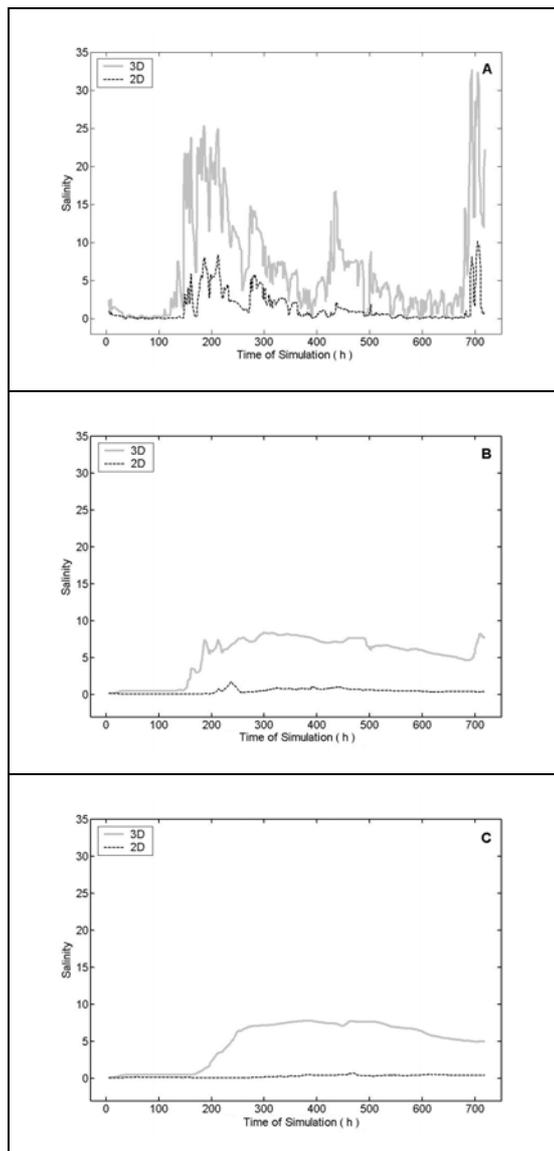


Figure 5 – Time series of salinity calculated by the two- and three-dimensional models at points 1 (A), 2 (B) and 3 (C).

Horizontal and Vertical Stratification in Saco da Mangueira

In a preliminary approach, results from the three-dimensional simulations were processed in terms of horizontal and vertical sections in order to evaluate the salinity dynamics between Saco da Mangueira embayment and the main estuary. Figures 6 and 7 illustrate one particular flood event ($t=715$ h). Figure 6 presents the horizontal distribution of salinity at the bottom, illustrating flood currents driving salinity excursion into the estuarine main channel and low salinity waters

being driven from the embayment towards the main channel. During this period, the dynamics of the embayment is controlled by the action of winds from the south quadrant. Winds from the SW promote flood fluxes in the estuary, when the remote wind effect piles water towards the coast forcing salt water landwards due to a barotropic pressure gradient (MÖLLER *et al.*, 1996; 2001). This same wind generates an ebb flow towards the main channel due to the local effect, piling up water at the entrance of the embayment. Weaker winds can reverse the barotropic pressure gradient, favoring the penetration of salty water in the embayment.

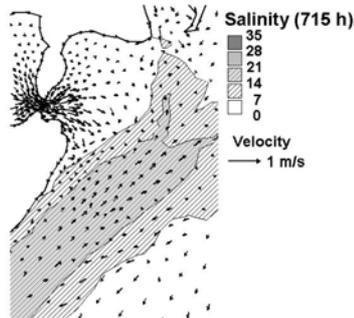


Figure 6 – Horizontal distribution of salinity at the surface and velocity vectors for $t=715h$.

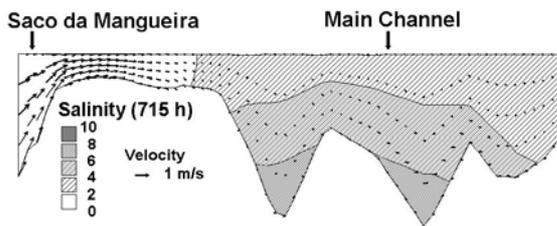


Figure 7 - Vertical cross-section at the entrance of the embayment showing the salinity distribution and velocity vectors for $t=715h$.

Figure 7 presents a vertical cross-section at the entrance of the embayment during this particular event, illustrating ebb currents around 0.3 m s^{-1} forcing low salinity waters towards the main channel, and establishing a stratified condition. These results are in agreement with MONTEIRO *et al.*, (*in press*).

In order to analyze the horizontal stratification inside Saco da Mangueira, time series of salinity were extracted from three-dimensional simulations at three points along the main axis of the embayment (Figure 8). Results clearly illustrate higher variability on the data extracted from point 1 then for points 2 and 3, with calculated variances of 45.5, 7.6, 8.2, respectively, and salinity gradients of up to

15 units. Although points 2 and 3 present very similar salinity time series, there is an evident time lag in the response of the system ($t=150 \text{ h}$ e $t=250 \text{ h}$, for example). These results are in agreement with PERSICH (1993).

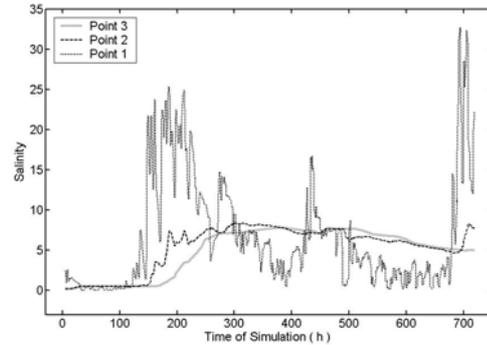


Figure 8 – Time series of mean salinity calculated by the three-dimensional model at points 1, 2 and 3 inside Saco da Mangueira.

Results also indicate that at the entrance of the embayment the salinity signal is modulated by the tidal and subtidal oscillations controlling the dynamics in the main access channel, whereas in the inner parts of the embayment (points 2 and 3), the influence of these oscillations is not observed. Furthermore, once salinity reaches these inner limits, the system tend to remain salty, with variations in salinity being determined by the passage of weather fronts. This is an indication that the embayment acts as a storage system with considerable residence times, which is likely to be related with the high biological productivity and eutrofization observed in the area (BAUMGARTEN *et al.*, 1995 and PERSICH *et al.*, 1996). Longer numerical simulations would be required to investigate this hypothesis.

CONCLUSIONS

Results presented here clearly illustrate the necessity of applying a three-dimensional model to properly investigate the dynamics, and consequently the associate mixing and transport processes, of a shallow embayment in the Patos Lagoon estuary.

The excursion of salt in Saco da Mangueira presents a time lag in relation to the excursion of salt in the main channel. Salinity tend to penetrate in the embayment when winds from the SW become weaker.

Strong horizontal stratification can be observed throughout the embayment, with

salinity gradients changing direction as a function of ebb and flood currents;

The area where the embayment connects to the main channel presents higher salinity variability and vertical stratification, while the inner limits are less affected by the dynamics of the channel.

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