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**Conference Paper** · October 2014

DOI: 10.13140/2.1.5054.4649

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Proceedings of the 17th Physics of Estuaries and Coastal Seas (PECS) conference,
Porto de Galinhas, Pernambuco, Brazil, 19–24 October 2014

# The impact of different forcing agents on the residual circulation in Baía de Todos os Santos, Brazil 13°S

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*Keywords*: *residual circulation, forcing agents and Todos os Santos bay*

**SUMMARY**

This study investigates the forcing of the residual circulation in Baía de Todos os Santos (BTS), surrounded by the third largest metropolis in Brazil. The Regional Ocean Modeling System (ROMS) was used to investigate the roles of the tide (TD), wind (WN), net heat flux (HF), freshwater flux (WF) and river discharge (RD) on the residual circulation. We forced the model in the boundaries with tidal elevations and currents from the global tidal model TPX07.2, and at the surface with wind stresses, fresh water and heat fluxes from a combination of NCEP/Reanalises and data from local weather stations. The modeled tidal circulation agrees well with current observations (mean percentage absolute deviation = 17%). The residual velocities have magnitudes smaller than 0.09 m/s. The flow is structured at the by moth with a net-landward flow (positive) in the channel centre and a net-seaward flow on the shoulders for all scenarios (Figures 2a, b and c) but that including the river discharge (Figure 2d). The lateral stratification associated with residuals currents, when forced by TD, WN+TD and HF+WF+WN+TD, is similar to that reported by Xavier (2002) running a barotropic model, and also in good agreement with analytical solutions presented by Li & O'Donnell (2005) for short ($4*L/\lambda < 0.6$) channels like the BTS. Adding river discharge to the model (Figure 2d) results in a vertically sheared residual flow across most of the channel, with flow magnitudes similar to that created by the other forcing. The results show that the tide is the main agent on the RC, however, the river discharge can significantly modify it.

## 1. INTRODUCTION

The Baía de Todos os Santos (BTS) is a well mixed, tidally driven estuary in Northeastern Brazil (12°50' S). It is the Brazilian second largest bay (1233 km$^2$) and is surrounded by the third biggest metropolis in the country (2.8 million people) (IBGE, 2014), which creates several localized domestic and industrial pollution hot spots. The BTS harbours several small estuaries, coral reefs and a diversity of sedimentary environments (Cruz, 2008, Barros et al., 2009 and Lessa & Dias, 2009). The bay also spans more than 100 km westwards from the humid coast, reaching the fringes of a semi-arid climate belt. Therefore, strong precipitation/evaporation gradients exist across the bay.

Transport wise, the connectivity of the sectors within the bay and between the bay and the continental shelf is regulated by the residual circulation (RC), which has been studied by Xavier (2002), Cirano & Lessa (2007) and Pereira & Lessa (2009). Xavier (2002) used a barotropic numerical model to study the influence of the tide and wind on the RC and residence time in the BTS. At the bay entrance, the author found a residual inflow in the channel and an outflow on the shoals, both with velocities close to 0.1 m/s. The wind influence was limited to the 0.5 m upper layer and the residence time grew from 0 (bay entrance) to 30 days (inner most section). However, Cirano & Lessa (2007) and Pereira & Lessa (2009), using an observational data set collected from several stations inside the bay, both in the dry and the wet seasons, encountered a permanently sheared vertical flow (~0.05 m/s) typical of an estuarine gravitational circulation. Pereira & Lessa (2009) also indicated that an inverse estuarine circulation can develop in the dry summer months, when higher salinities and relatively small water temperatures occur in a restrict sector of the bay (Baía de Aratu).

The RC can be established by barotropic and baroclinic gradients. While the former is mainly generated by tides and wind (local and remote), the latter is a result of heat fluxes and water balance due to both atmospheric and riverine water inputs and evaporation. The role of these different forcing agents have been investigated both in positive and negative estuaries. Weisberg & Zheng (2006) investigated the roles of the tide, rivers and wind on the flushing time and estuary-ocean exchanges in positive Tampa Bay, and concluded that the baroclinic circulation is as important as the wind on the circulation and flushing time during the autumn. Negative estuaries such as Gulf of Saint Vincent (De Silva Samarasinghe et al., 2003) and Spencer Gulf (Teixeira, 2010), however, may undergo a reduction, or even stagnation, of the bay-ocean exchange during the summer. The phenomena are ascribed to increases in the bay temperature that reduces, or extinguishes, the density gradients established between those compartments. Hydrologically, the BTS may swing seasonally between a negative and a positive regime, and inverse estuarine conditions can be observed during the late summer months (Pereira & Lessa, 2009; Oliveira, 2014). Therefore, the importance of the fluvial discharge, heat balance and water balance vary significantly not only seasonally but also inter-annually. This work aims to quantify, based on results of numerical simulations, the importance of the forcing mechanisms tides, wind, net heat flux, net water flux and river discharge on the RC of the BTS, and investigate there seasonal variation.

## 2. METHODS

The Regional Ocean Modeling System (ROMS) was chosen to simulate the flow in the BTS. The model was implemented with a 500 m horizontal resolution grid, higher than that suggested by Zimmerman (1986) considering the bay tidal excursion, and 20 sigma layers. The grid covers the entire BTS area, the distal region of its tributaries and the adjacent shelf and slope down to 1418 m. The model was forced in the open boundaries with tidal elevations and currents from the global tidal model TPX07.2 and also with monthly climatological mean of velocities, temperature, salinity and elevation calculated from HYCOM/NCODA solutions with 1/12º horizontal resolution. At the surface, wind stress, fresh water flux and heat flux were obtained from a combination of NCEP/Reanalises and climatological averages from local weather stations. The heat flux was corrected using month-averages of sea surface temperatures from a 10 years (2003-2012) MODIS satellite time series. Finally, the climatological discharges of the three largest rivers that flow into the BTS were also set as model input. The barotropic and baroclinic time steps were ~2.7 s and 80 s, respectively, and the simulation time was 4 years, from which only the last year was analyzed.

Four incrementally complex experiments were conducted, combining tides (TD), wind (WN), heat flux (HF), water flux (WF) and river discharge (RD). The first experiment was forced with tides only, and compared with Xavier's (2002) results. The second experiment used WN+TD to identify the role of the wind on the tidal RC. The third experiment involved HF+WF+WN+TD, from which the importance of the HF+WF is calculated. The last experiment contemplated all of the forcing agents, i.e., RD+HF+WF+WN+TD, and investigates the baroclinic contribution of the RD to the RC. It is also the control experiment used to validate the RC against the results presented by Cirano & Lessa (2007). It is important to mention that the Paraguaçu River discharge, responsible for 70% of the discharge debouching into the bay, reaches its peak (160.5 $m^3/s$) in the summer (Dec), when rainfall over the bay (WF), and the discharge from its smaller tributaries, is at a minimum.

## 3. RESULTS AND DISCUSSION

The results from the experiment with all forcing agents (RD+HF+WF+WN+TD) were compared to observations collected with an ADCP during January of 1999 at the bay entrance. Depth-averaged currents agree well in magnitude and phase, although a small overestimation of the flood currents (positive values) during spring tides occur (Figure 1). The Mean Percentage Absolute Deviation (MPAD) was equal to 17%.

The spatial structure of the RC at a cross-section at the entrance of the bay was used to quantify the importance of the forcing agents on the water exchange between the bay and the shelf. The results from four experiments for the month of January, the second highest river discharge and when the winds is mostly transversal to the N-S estuary's axis, are presented in Figure 2. For all experiments, the residual velocities presented magnitude smaller than 0.09 m/s. The average magnitudes for the four experiments in sequence were: 0.03, 0.02, 0.02 and 0.03 m/s. The flow is structured with a net-landward flow (positive) in the channel centre and a net-seaward flow on the shoulders for all scenarios (Figures 2a, b and c) but that including the river discharge (Figure 2d). The lateral stratification associated with residuals forced by TD, WN+TD and HF+WF+WN+TD was similar to that presented by Xavier (2002) running a barotropic model, and also in good agreement with analytical solutions presented by Li & O'Donnell (2005) for short (4*L/λ < 0.6; L=estuarine length, λ=tidal wave length) channels like the BTS. Adding river discharge to the model (Figure 2d) resulted in a vertically sheared residual flow across most of the channel, with flow magnitudes similar to the other model runs.

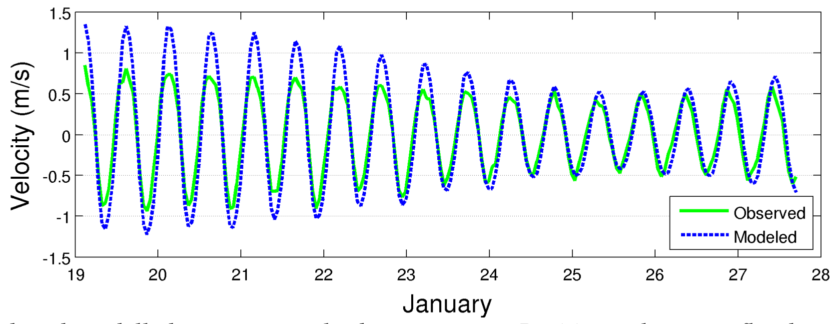


*Figure 1: Observed and modelled currents at the bay entrance. Positive values are flood currents and negative values are ebb currents.*

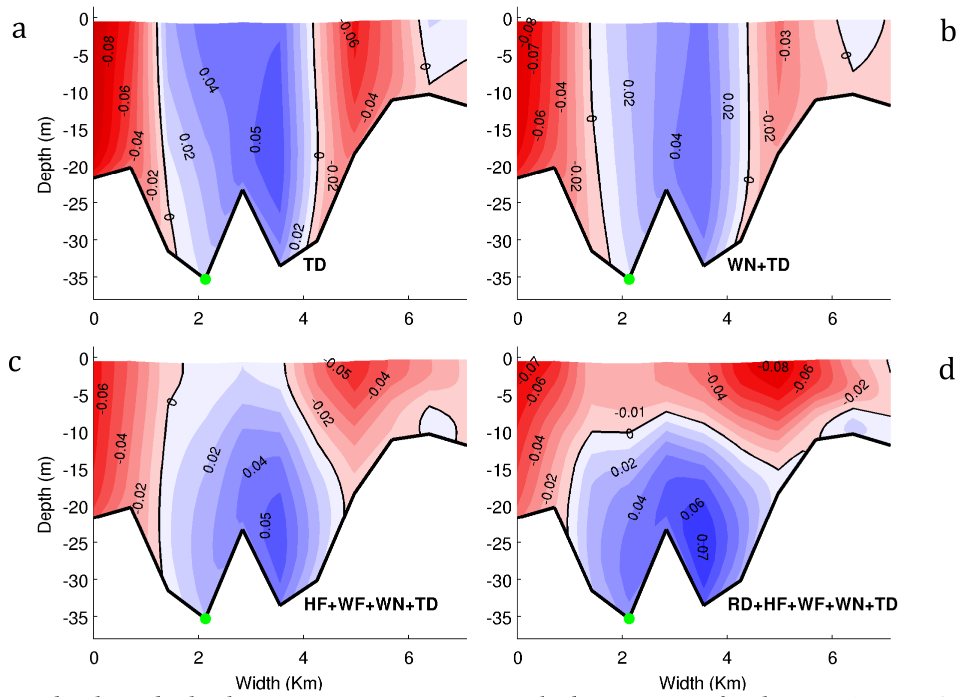


*Figure 2: Longitudinal residual velocities in a cross-section at the bay entrance for the experiments: (a) - TD; (b) - WN+TD; (c) - HF+WF+WN+TD and (d) - RD+HF+WF+WN+TD. The graphs are looking into the estuary where positive (blue) values are inflow and negative (red) are outflow. The green dot show the ADCP location associated with the data shown in Figures 1 and 3.*

The results show that the river discharge within the BTS is important for establishing the gravitational circulation described for the summertime by Cirano & Lessa (2007), at the bay entrance (Figure 3a). The lack of riverine discharges in the model set up results in laterally-sheared flows even during the wet season (not shown). The inclusion of river discharges creates a vertically-sheared flow, less conspicuous in the wet season but with an indication of a three layered flow (Figure 3b) ascribed to southern winds (Lessa et al 2009), though with lower magnitudes in the model set up. The subdued vertically-sheared flow in the wet season is ascribed to small longitudinal density gradients generated by the model, which apparently needs to incorporate the drainage of the peripheral catchment area (1700 km2). Finally, the simulations show that the tide produce the largest RC, however, the river discharge can significantly modify and enhance its pattern and magnitude, respectively.

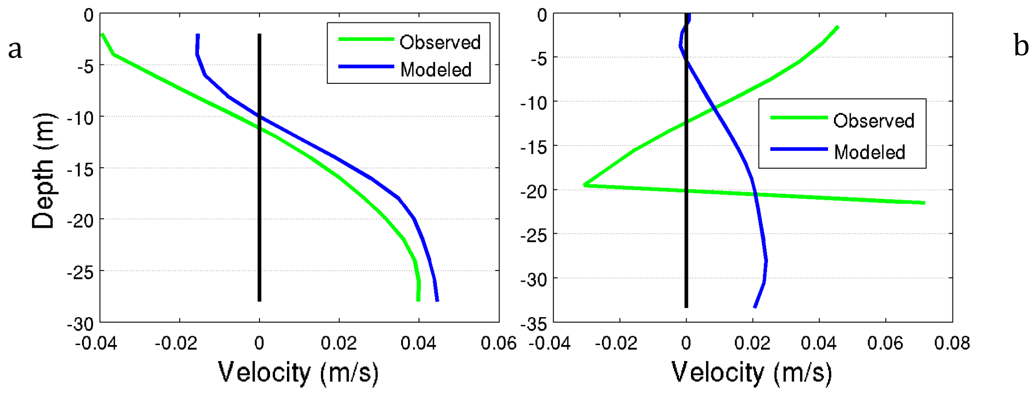


*Figure 3 - Vertical profile of the residual longitudinal velocities at the BTS entrance for dry (a) and (b) wet seasons. Positive values are inflow and negative values are outflow.*

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