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Invited feature

Fortnightly switching of residual flow drivers in a tropical semiarid estuary

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A B S T R A C T

Current velocity and hydrographic measurements were obtained in Mossoró estuary, a tropical semiarid estuary in Northeastern Brazil, to explore the hydrodynamic regime associated with marked seasonal variability in evaporation and precipitation. Measurement campaigns were performed during dry conditions in October 2012 and wet conditions in May 2013. Dry season observations showed along-estuary density gradients of order 0.001 kg/m^4 with salinity increasing upstream in the first 20 km up to a value of 70 g/kg. Salinity then decreased to a value of 48 g/kg at the upstream limit of the section. During this dry season, the residual flow structure changed drastically from spring to neap tides. Neap tide residual flows showed inflow of oceanic water at the surface and outflow of hypersaline water underneath. Spring tide residual flows showed net inflow throughout the water column in the middle of the section and outflow over the flanks, a laterally sheared structure consistent with tidally induced residual flows. In the wet season, along-estuary density gradients were of similar magnitude to the dry season but in the opposite direction. Residual flows in neap tides were as expected for density-driven flows: outflow at surface and inflow underneath. During spring tides, residual flows were dominated by outflows over the flanks and inflow in the middle of the section, once again consistent with tidally driven residuals. Advective accelerations from tides were compared to baroclinic pressure gradients, in the non-dimensional tidal Froude number (Fr_0), to explore the changes from tidally driven to density-driven residual flows. Results indicated that residual flows in this estuary were driven by tidal rectification ($Fr_0 >> 1$) in spring tides and by density-gradients ($Fr_0 << 1$) in neap tides. Thus, estuarine residual flows switch from density-driven in neaps to tidally driven in springs. In general, it is proposed that the switch can be diagnosed with Fr_0.

1. Introduction

The influence of fortnightly forcing by tides on residual flows, or exchange flows, has been documented extensively (e.g. Linden and Simpson, 1986; and review by MacCready and Geyer, 2010). When baroclinic pressure gradients are the main drivers of residual flows, neap tides allow the development of more vigorous exchange flows relative to spring tides because of reduced vertical mixing (e.g. Nunes and Lennon, 1987; Nunes Vaz et al., 1989; Geyer and Cannon, 1982). In estuaries with lateral variations in bathymetry, density–driven exchange flows may be laterally sheared, instead of vertically sheared, and consist of inflow in the channel and outflow over the shoals (e.g. Wong, 1994). But this exchange flow structure can vary depending on how frictional the basin is, as characterized by the competition between frictional effects and Coriolis accelerations (Kasai et al., 2000). Such competition is expressed in terms of the Ekman number *Ek*. Under weak frictional conditions ($Ek << 1$) the exchange flow can be vertically sheared.

In contrast, more robust residual flows appear in spring tides than in neap tides when tidal forcing is the main driver of residual exchange (Li and O'Donnell, 2005). This is because spring tides produce larger tidal rectification than neap tides (e.g. Valle-Levinson et al., 2009). Tidally driven exchange flows can display inflow in the channel and outflow over shoals, just like density-driven flows (Valle-Levinson et al., 2009). This structure, however, is restricted to 'short' estuaries where the length of the basin is less than approximately 17% the tidal wavelength (Li and O'Donnell,

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2005). In these 'short' estuaries tidal regimes consist of water elevation and currents being near quadrature (e.g. Friedrichs, 2010). In 'long' basins, the tidal residual flow reverses and the inflow appears over shoals (Li and O'Donnell, 2005).

Density–driven exchange flows will therefore tend to be in opposite directions to tidal residual flows in hyperpycnal (water density increases landward; Largier, 2010), 'short' estuaries. Hyperpycnal estuaries represent suitable natural laboratories to study such competition between density-driven and tidally driven flows, as long as the ratio of tidal amplitude to depth is greater than 0.1. This is because the ratio indicates non-linear influence from tidal forcing (e.g. Parker, 1991; Speer and Aubrey, 1985) and the likelihood for tidal forcing to drive residual flows (Pingree and Maddock, 1977). The objective of this study was to explore a possible switch of predominant forcing, from density-driven (linear dynamics) to tidally driven (non-linear dynamics), in the residual flows of an estuary. This objective was pursued with observations in Mossoró estuary, a tropical system of Northeastern Brazil. This region is subject to marked dry and wet seasons so that coastal bodies of water become hyperpycnal in the dry season and hypopycnal (density increases seaward) in the wet season. This seasonality allowed the exploration of tidal and buoyancy forcings acting in concert or in opposite directions. Through the comparison of scaled tidal forcing to baroclinicity, it was found that the former dominates in spring tides and the latter prevails in neap tides. This is the first study that describes physical processes in Mossoró estuary and may be the first one that observationally documents the fortnightly switching of dominant forcing, at least during the period of observations.

2. Study area

The tropical estuary studied was Mossoró, which is one among two dozen estuaries along the coast of the states of Ceará and Rio Grande do Norte (e.g., Frota et al., 2013) in northern Brazil (Fig. 1). These estuaries are on average < 50 km long and <5 m deep. They are located in a semi-arid climate with well distinguished wet (Feb–May) and dry (Aug–Nov) seasons (Fig. 1). The annual water budget displays a short period of surplus caused by tropical rainfall. In the rest of the year, evaporation exceeds precipitation. The annual evaporation rate is 2 m, while precipitation is 0.85 m/year. During the dry season most estuaries of the region receive no freshwater inflow and become hypersaline and hyperpycnal (e.g. Largier, 2010). In the wet season, these estuaries tend to display hyposaline and hypopycnal conditions, typical of systems in temperate latitudes (Largier, 2010).

Mossoró estuary is located at 4.96°S and 37.14°W and has a drainage basin of 14,200 km^2 with extensive evaporative ponds for salt exploitation. The estuary is roughly oriented N–S but a couple of meanders make its orientation change along its course (Fig. 1). The estuary is 50 km long, varies from 50 to 300 m wide, and displays variable maximum depths from around 7 m at the mouth to 1–2 m at the upstream reaches. Annual river input into the estuary averages <10 m^3/s, which peaks in April and May at ~30 m^3/s. In fact, river discharge typically occurs between March and June at monthly averages >5 m^3/s. The rest of the year has monthly mean discharges <5 m^3/s with periods of no discharge. Isolated pulses may exceed 10 m^3/s during the wet season. Tides in the estuary are predominantly semidiurnal, showing ranges of $\approx$3 m at spring tides and 1.5 m at neap tides. Tides are asymmetric because the ratio of semidiurnal to quarterdiurnal (M_2/M_4) harmonics for tides and currents is ~0.15 in spring tides and ~0.05 in neap tides. The ratio of semidiurnal to sixthdiurnal (M_2/M_6) harmonics is ~0.06 in springs and ~0.08 in neaps. Tidal nonlinearities are therefore expected to affect the dynamics of the estuary.

The study area is influenced by the Intertropical Convergence zone in the wet season but is just south of this zone in the dry season. Winds in the region tend to be related to the easterly "trade winds" but their influence inside the estuary is irrelevant, at least during the observation periods. Effects of coastal ocean (remote) forcing on the estuary require relatively longer time series than those obtained in this study and therefore remain unknown.

3. Methods

3.1. Data Collection

Measurement campaigns were performed during dry conditions on October 15–23, 2012 and under wet conditions on May 3–12, 2013. Each campaign included measurements of along-estuary hydrographic sections over 35 km. These were complemented by week-long time series of current velocity profiles and salinity-temperature signals at different depths. Along-estuary hydrography sections and time series measurements were combined with tidal-cycle surveys of current velocity and hydrographic profiles in spring and neap tides.

A longitudinal hydrographic transect was sampled in the dry season on October 19th, 2012 with a YSI Castaway Conductivity-Temperature-Depth (CTD) recorder operating at 5 Hz. This instrument has an accuracy of 0.1 g/kg in salinity and 0.05 °C in temperature. Hydrographic profiles were recorded at intervals of 1 km along a ~35 km transect starting at the estuary's mouth. The extent of measurements in the longitudinal transect was restricted by shallow bathymetry, but the estuary ends further upstream at a dam. The transect was occupied around high tides and took approximately 1.5 h to complete. The same sampling strategy was used on May 11th, 2013 during the wet period. In this period, the longitudinal transect was sampled with a JFE Advantech *Rinko* CTD that has an accuracy of 0.01 g/kg for salinity and 0.01 °C for temperature.

Moored instruments consisted of bottom-mounted acoustic Doppler current profilers (ADCPs) and conductivity-temperature data loggers. A 1000 kHz Nortek current profiler Aquadopp was deployed at a mean depth of 5.5 m in both dry and wet periods. The instrument was placed approximately 2 km from the estuary's mouth. Profiles were recorded every 10 min with a vertical resolution (bin size) of 0.35 m, starting at 0.75 from the transducers. The ADCP transducers were ~0.2 m from the bottom so the first bin was 0.95 m from the bed. Salinity time series were recorded near the bottom, next to the ADCP, with a JFE Advantech *Infinity* WCT Data logger, recording at intervals of 5 min. Moored instruments were deployed from 13:40 on October 15th to 11:15 on October 26th, 2012, and from 16:00 on May 3rd to 11:10 on May 12th, 2013. All times are UTC.

During both seasons a 1200 kHz acoustic Doppler current profiler (ADCP) was towed along one cross-estuary transect for 12.5 h. Sampling in the dry season occurred on October 17th (spring tides) and October 23rd (neap tides), 2012. The length of the transect was ~200 m and its location was ~2 km from the estuary's mouth. The transect was sampled 61 times in spring tides and 123 times in neap tides. The difference in number of transect repetitions simply had to do with an adjustment of the measurements strategy. Velocity profiles were recorded every 0.4 s at vertical bins of 0.25 m, while the ADCP was towed at ~1 m/s. Ten velocity profiles were averaged to reduce the noise of the measurements, giving a spatial resolution for transect velocity profiles of around 4 m. In the wet season, towed ADCP surveys were carried out on May 4th (neap tides) and May 10th (spring tides), 2013 with the same approach as in the dry season. In the wet season, the sampling transect was covered 127 times during neap tides and 147 times in spring tides.