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Interplay between river discharge and tides in a delta distributary

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ABSTRACT

The hydrodynamics of distributary channels has tremendous impact on nutrient and dissolved oxygen circulation, transport of sediments, and delta formation and evolution; yet many processes acting at the river–marine interface of a delta are poorly understood. This paper investigates the combined effect of river hydrograph and micro-tides on the hydrodynamics of a delta distributary. As the ratio between river flow to tidal flow increases, tidal flood duration at the distributary mouth decreases, up to the point when flow reversal is absent. Field measurements in a distributary of the Apalachicola Delta, Florida, USA, reveal that, once the flow becomes unidirectional, high-discharge events magnify tidal velocity amplitudes. On the contrary, while the flow is bidirectional, increasing fluvial discharge decreases tidal velocity amplitudes down to a minimum value, reached at the limit between bidirectional and unidirectional flow. Due to the different response of the system to tides, the transition from a bidirectional to a unidirectional flow triggers a change in phase lag between high water and high water slack. In the presence of high riverine flow, tidal dynamics also promote seaward directed Eulerian residual currents. During discharge peaks, these residual currents almost double mean velocity values. Our results show that, even in micro-tidal environments, tides strongly impact distributary hydrodynamics during both high and low fluvial discharge regimes.

1. Introduction

Flow dynamics in delta distributaries determines the fate and transport of sediments, contaminants, and nutrients with important consequences for deltaic deposits, landform evolution, water quality, and deltaic ecosystems [e.g. [14,16,19,35,40]] . Herein we investigate the effect of micro-tides on the hydrodynamics of a delta distributary. We particularly focus on the interactions between tides and river hydrograph, and on the system response to tides under low and high riverine discharge conditions. Three main aspects of the problem have been taken into account: (i) phase delay between water level and velocity fluctuations; (ii) tidal velocity amplitudes; (iii) tidally induced Eulerian residual currents. These processes are investigated by means of a two months duration instruments deployment in Apalachicola Bay, Florida, USA, where velocity and water level measurements have been collected at the mouth of a delta distributary, and along its reaches, during two consecutive flooding events.

The effect of tides has been recognized as an important factor controlling both the hydrodynamics of the jet exiting river mouths and the morphology of its sediment deposits [e.g. [8,13,20,31,48,52]]. Interactions between tidal oscillations and riverine runoff have been also closely related to water quality, and nutrient concentrations [e.g. [36]]. The presence of tides has three main consequences: mixing is increased, and the effect of buoyancy is partially suppressed; a bidirectional sediment transport is present; the marine-river interface moves in both the vertical and horizontal direction [e.g. [51]]. When tides enter the river they behave as waves progressing upstream, they distort, and eventually dissipate due to bottom friction and riverine flow. For a bidirectional flow and a propagating tide, the effect of river discharge on tidal amplitude, wave celerity, and phase lag has been explored [e.g. [6,7,48]]. It has been shown that the presence of a river discharge has the same effect than increasing friction by a factor proportional to the riverine to the tidal discharge ratio. Thus, increasing river discharge enhances tidal damping, reduces tidal velocity amplitude, and wave celerity, and increases the phase lag between high water and high water slack [e.g. [5,7]].

However, many aspects of the interaction between tidal hydrodynamic and riverine flow deserve further investigations.

Another important mechanism, connected this time to different riverine discharge conditions, is the backwater effect, which could have important geomorphological implications, when combined with tidal changes in water level. This backwater effect can be also referred to as residual slope [e.g. [7,43]]. For a gradually varied

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Nomenclature

Q_R	river discharge
B	distributary mouth width
b	convergence length of the stream width
h_{msl}	water depth at mean sea level
h_{FLOOD}	water depth during flood
h_{FLOOD}	water depth during ebb
H	tidal range (from HW to LW)
H'	slack tidal range (from HWS to LWS)
HW	high water
HWS	High water slack
LW	low water
LWS	low water slack
O	surface area of the distributary channel where the tide propagates
P	tidal prism volume
u_0	velocity due to the river discharge
Δu	difference between tidally averaged velocities for different discharge values
δ	damping coefficient
ε	phase lag between HW and HWS
Φ_z	water level phase
Φ_u	velocity phase
v	tidal velocity amplitude
v_{EBB}	difference between ebb velocities and velocities at mean sea level
v_{FLOOD}	difference between flood velocities and velocities at mean sea level

flow, velocity varies along the channel; consequently bed slope, water surface slope, and energy line slope all differ from each other, and a backwater profile establishes. For instance, in a subcritical flow, the effect of a control point, such as the sea level at the downstream boundary, propagates upstream creating a water profile that gradually adapts to the downstream conditions. For low flow conditions, the water depth at the shoreline is greater than the normal flow depth, and the water surface profile is concave up (also referred to as M1 curve, Fig. 1, green line). On the contrary, a drawdown profile (also called M2 curve, Fig. 1 pink line) is typically established during high flow conditions, when the normal flow depth is higher than the water depth at the shoreline [e.g. [11,29]].

2. Study site

The lower Apalachicola River is located in the Florida panhandle at the terminus of the Apalachicola-Chattahoochee-Flint (ACF) River system (Fig. 2a). Apalachicola River is the largest in Florida in terms of flow rate and it belongs to one of the largest river system in the Gulf of Mexico. The system was formed over the past 6000 years as the Apalachicola River deposited sediments into a shallow shelf, the distal sands of which were reworked to form sandy barriers, spits, and islands [39]. The bay encompasses about 620 km^2 of open water with an average depth of 1.9 m at mean low tide. Approximately 80% of the open water zone is composed of soft, muddy, unvegetated sediments and the remainder is divided between oyster reefs and submerged aquatic vegetation [9,23]. Hydrodynamics forcing observed here are likely to be present in other river mouth settings along the Gulf Coast as they are linked to regional meteorological and oceanographic conditions [1,42]. The northern Gulf Coast experiences winter cold fronts that reoccur with a 3–10 day periodicity. During the approaching phase of the front, onshore winds force water and sediment landward. After the front passes, winds shift to the north, leaving behind mudflats and other coastal deposits [1,15,42]. Discharge in the Apalachicola River has ranged between 110 and 8235 m^3/s from 1929 to present; peak flows generally occur in late winter and early spring, and are highly correlated to rainfall events in Georgia, while low flows occur during late summer and early fall [9,17]. During the period of our study, river discharge ranged from 200 to 3100 m^3/s.

Tides in Apalachicola Bay are mixed diurnal and semi-diurnal. The two main semidiurnal components are the lunar semidiurnal (M2), and solar semidiurnal (S2), with amplitudes (half the tidal range) equal to 0.38 and 0.12 m respectively. The two main diurnal components are the two lunar constituents (K1 and O1), with amplitudes equal 0.43 and 0.37 m respectively.

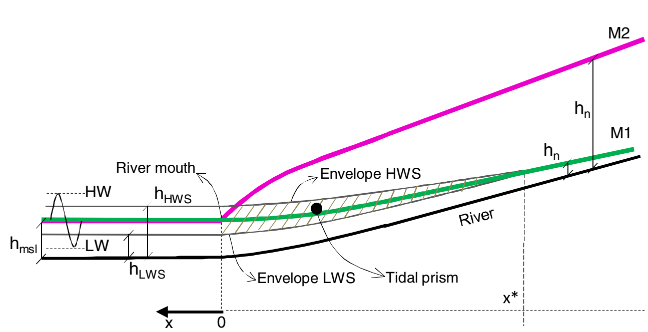

Fig. 1. Sketch of the geometry of an idealized distributary channel. Water levels at mean sea level in case of high (pink line) and low (green line) fluvial discharge. The longitudinal axis, *x*, has origin at the river mouth and is positive in the seaward direction. The longitudinal coordinate, x^*, is the point up to which the tide propagate. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

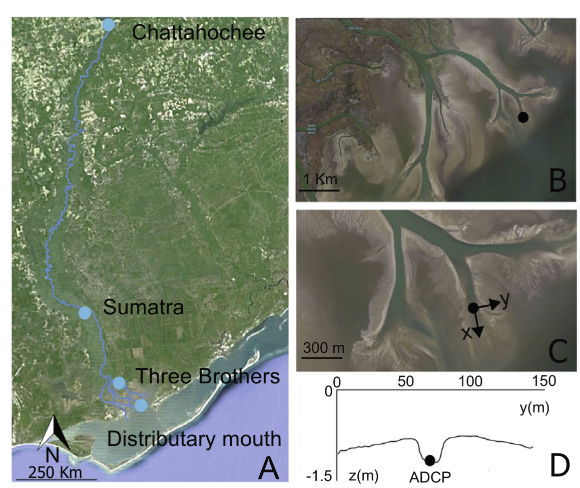

Fig. 2. (A) Study area in the Apalachicola delta, Florida. Location of instruments deployment: ADCP deployed at 29°45′29.44″N, 84°54′43.02″W; RBR deployed at 29°47′58.99″N, 84°59′16.66″W, near the Three Brothers Creek. USGS stations near Sumatra (ID 02359170) and near Chattahochee (ID 02358000); (B) and (C) distributary mouth and location of ADCP deployment; (D) cross section of the river mouth, the black point indicates the ADCP location, at the bottom of the distributary.