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Estuarine and sediment dynamics in a microtidal tropical estuary of high fluvial discharge: Magdalena River (Colombia, South America)

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ABSTRACT

Relation among estuarine processes, mixing mechanisms and turbidity maximum zone (TMZ) formation was evaluated in a microtidal tropical estuary of high fluvial discharge (Magdalena River, northwestern South America). Particularly, assessing the effects of vertical stratification over mixing, estuarine circulation and suspended sediment transport processes. Measurements of salinity, temperature, density, currents and suspended sediment concentration (SSC) were performed at the Magdalena river mouth during high and low streamflows to distinguish among two contrasting seasonal conditions (flow conditions, wind patterns, wave energy). Salinity, temperature, density and location of the freshwater-saltwater interface (FSI) exhibited a sharp seasonal variability. The river mouth and delta front were stratified regardless of the hydrologic season, whereas the riverine section was stratified during the low streamflow season, reflecting the balance between fluvial advection and vertical stratification. Reduction of the vertical mixing led to a more clearly defined and extended stratification. Bottom friction is the main mixing mechanism, but as stratification is strengthened along the river mouth, the vertical mixing weakens, promoting the developing of TMZ (SSC $> 4500\ \mathrm{mg\,l^{-1}}$). Our results indicate that TMZ developing is caused by the convergence of stratified layers near the nodal point and the weakening of bottom turbulence by stratification. Although the TMZ exhibited a strong seasonal variation in its magnitude and extent, it usually formed in the convergence front demarcated by saltwater intrusion. Streamflow is the major influence on the TMZ formation since it allows the development of stratified conditions, which weaken turbulent mixing, and thus promotes particulate matter settling. The Magdalena River estuary can be classified as turbid ($4000\ \mathrm{mg\,l^{-1}} < SSC_{max} < 10{,}000\ \mathrm{mg\,l^{-1}}$) and extremely turbid during low streamflow seasons ($SSC_{max} > 10{,}000\ \mathrm{mg\,l^{-1}}$). These values are of the same order as the SSC reported for the Yangtze and Yellow estuaries, classified as having the largest SSC values of the world.

1. Introduction

Estuaries are considered among the most vulnerable systems of the world as a result of global change and the intensification of extreme events. These coastal areas might experience dramatic changes within the next years, expecting unforeseen consequences for natural and social systems (Syvitski and Saito, 2007). In comparison with meso- and macro-tidal estuaries, micro-tidal estuaries have been less studied, except for those in the Mississippi (United States), Nile (Egypt), and Huang He (China) rivers (*e.g.* Skliris and Lascaratos, 2004; Wang et al., 2006; Lane et al., 2007). Thus, systematic and detailed information on the relationship among estuarine processes, mixing mechanisms and turbidity maximum zone formation, including the changes experienced at seasonal scales, is still required to obtain a comprehensive knowledge about these systems (Moskalski and Torres, 2012; Wu et al., 2012). Furthermore, recent studies highlight the regional importance of microtidal estuaries, regarding littoral morphodynamic balances and the transfer of nutrients toward the coastal zones (Hossain et al., 2001; Purnachandra et al., 2011).

Several authors highlight the great influence of fluvial regimes in tropical estuaries, especially of those experiencing microtidal ranges (Moskalski and Torres, 2012; Wu et al., 2012). Changes of freshwater discharge affect salinity distribution and gravitational circulation patterns, altering the sediment resuspension/transport/deposition cycles. During low frequency events of freshwater discharge, suspended sediment transport is usually high, which leads to considerable changes in

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the deposition patterns within the estuarine system. Furthermore, large amount of freshwater most often lead to a shift of the salt wedge to the prodelta and promote sediment flux toward the continental shelf. However, this sediment transfer process is highly regulated by estuarine morphology, sediment trapping efficiency and turbidity maximum zone dynamics (Prandle, 2009; Traini et al., 2012). The advection of water masses with different density as well as turbulence, generated within the boundary layers (bottom and halocline), both control flocculation and sediment trapping, leading to the formation of the turbidity maximum zone (TMZ). This zone, which exhibits highest suspended sediment concentrations within estuaries, plays a fundamental role in estuarine circulation and sediment/nutrient flux to the ocean (Dyer, 1994; Wu et al., 2012). Sediment trapping and TMZ formation are highly variable processes, depending on residual and gravitational circulation, mixing conditions and sediment properties. The way in which these processes interact, determine the dynamics of sediment trapping, the extension and structure of the TMZ and therefore the flux of sediments to the ocean (Dyer, 1994; Prandle, 2009). Usually, it is assumed that estuarine sediment dynamics is controlled by the interaction of tidal and fluvial currents, and the subsequent sediment resuspension/transport/deposition cycles. However, the contribution from salinity-induced stratification should not be neglected when analyzing sediment dynamics (Geyer, 1993; Wu et al., 2012). Especially in this context, seasonal variability of estuarine sediment dynamics in micro-tidal estuaries, such as the Magdalena River in northwestern South America (Fig. 1), deserves more attention.

This paper examines the main controlling mechanisms of the estuarine and sediment dynamics in the tropical, micro-tidal Magdalena River estuary with high fluvial discharge, considering two different seasonal conditions, which has not been done so far. Particularly, we focus on (*i*) determining spatial variability of the estuarine structure regarding saline-induced stratification, density and suspended sediment concentration, as well as its response to seasonal changes; (*ii*) analyzing vertical saline-induced stratification and density effects on mixing processes, estuarine circulation and suspended sediment transport; and (*iii*) identifying the dominant processes controlling sediment dynamics on seasonal scale. Furthermore, the description, interpretation, and prediction of the estuarine dynamics is of great importance, when considering subsequent effects with respect to morphological stability of estuaries and coastal adjacent zones, flux and fate of particle matter and biochemical substances, and ecosystem dynamics (Dyer, 1994).

2. Study area

The Magdalena River forms an arcuate delta, with an area of 1690 km^2. It is a fluvio-wave dominated delta. It receives a flux of 205.1 $km^3\,yr^{-1}$ of freshwater and 142.0 × 10^6 $t\,yr^{-1}$ of suspended sediment load, measured at Calamar hydrological gauging station (Fig. 1) (Higgins et al., 2016). Overall, the delta wave system is dominated by north-eastern swell with mean significant wave heights (H_s) of 2.2 ± 1.1 m and mean peak periods of 6.7 ± 2.3 s (Ortiz et al., 2013). However, these physical parameters experience a large seasonal variability. The dry season lasts from January to April with a mean streamflow and suspended sediment load of 4360.5 $m^3\,s^{-1}$ and 218 × 10^3 $t\,d^{-1}$, respectively (J.C. Restrepo et al., 2016). This season also exhibits high energy wave conditions (H_s > 2.5 m), caused by strong north-eastern directed trade winds and cold fronts (Ortiz et al., 2013). On the contrary, throughout the flood season, which extends from September to November, the mean streamflow and the mean suspended sediment load increases to 8063.1 $m^3\,s^{-1}$ and 531 × 10^3 $t\,d^{-1}$, respectively (J.C. Restrepo et al., 2016). During that time, the delta experiences low to moderate wave energy conditions (H_s < 1.5 m), with swells coming predominantly from the west and northwest (Ortiz et al., 2013). The main river mouth forms an estuary at Bocas de Ceniza (Fig. 1B), which experiences a diurnal mixed tide ranging from 0.48 m to 0.64 m during neap and spring tides, respectively.

The Magdalena's continental shelf is narrow due to deltaic progradation. It exhibits a ~0.1° slope gradient and displays widths between 2 and 26 km (Ercilla et al., 2002). The main river mouth is aligned with a large slope (~40°) submarine canyon at the continental shelf (Fig. 1). Morphology and architecture of this canyon is linked to the sediment input from the Magdalena River (Ercilla et al., 2002). Furthermore, they have proposed, that a large proportion of fluvial sediments directly deposit onto the continental slope. Total sediment accumulation in the prodelta corresponds to < 5% of the Magdalena's annual mean suspended sediment load, as calculated based on historic bathymetric geo-referred data (J.C. Restrepo et al., 2016). Deposition processes have led to the formation of a frontal mouth-bar and a large-scale subtidal shoal, at the east of the river mouth (Fig. 1). A minimum

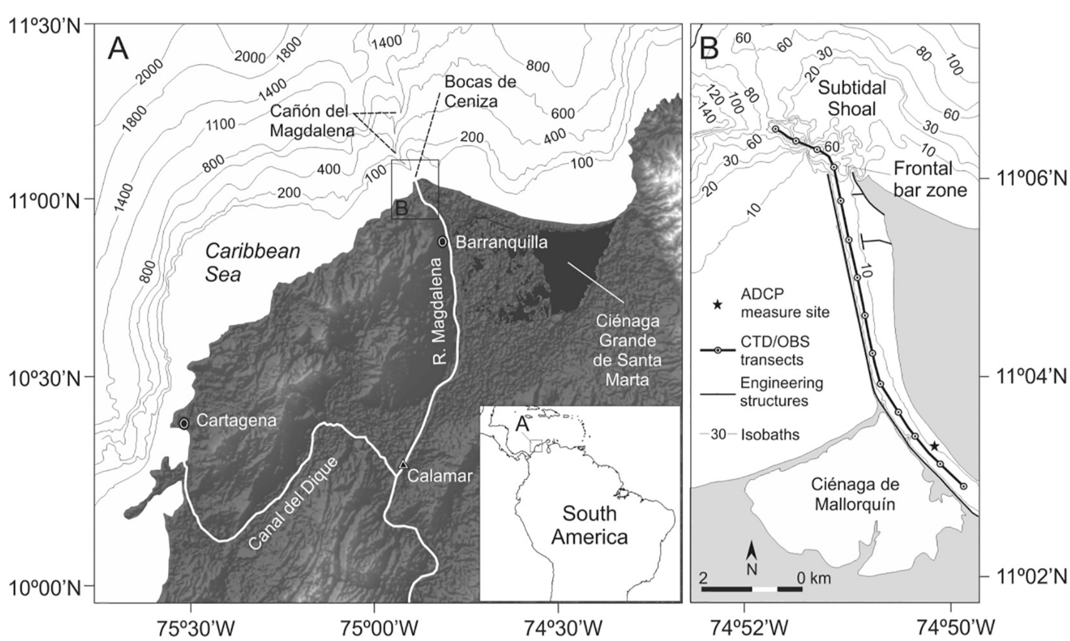

Fig. 1. Magdalena River Delta. General location, main bathymetric features and measuring sites.