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Factors Influencing the Distribution and Characteristics of Surface Sediment in the Bay of Cartagena, Colombia

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ABSTRACT

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This study evaluated patterns of coastal sediment movement and deposition under different seasonal conditions (warm and cold phases of the El Niño–Southern Oscillation [ENSO] and normal conditions) in Cartagena Bay, Colombia. A calibrated numerical model (MOHID modeling system) was applied to assess the spatial distribution of sediments transported by the Canal del Dique to the bay and studied the spatial distribution and major textural characteristics of 234 surface sediment samples. Currents in the Bay of Cartagena are controlled primarily by the strength and direction of the wind. Model results show major sediment deposition in the southern sector of the bay during the dry season. More homogenous spatial distribution of sediments throughout the Bay of Cartagena occurs with an increase in river inputs from the Canal del Dique. These patterns were enhanced or weakened, respectively, by cold and warm phases of the ENSO. Predominant sediments were medium size ($\varphi = 5.35 \pm 1.2$), poorly sorted ($\sigma = 1.63 \pm 0.8$), with notable asymmetry ($Sk = -0.052 \pm 0.2$) and kurtosis ($k = 0.84 \pm 0.4$). Sediments with lower sand content (<5%) are located along a latitudinal axis from the Canal del Dique delta to the western end of the island of Tierrabomba. $CaCO_3$ content of the sediments is <10%. Water and sediment flow, controlled by the Canal del Dique, has favored the transport and deposition of poorly sorted, symmetric, and mesokurtic mud in most of the Bay of Cartagena. As a result, autogenous calcareous sediments have been covered by fine terrigenous sediments that were delivered via the Canal del Dique. Thus, the channel plays a more prominent role in sediment transport and deposition in the Bay of Cartagena than thought previously.

ADDITIONAL INDEX WORDS: *Littoral circulation, suspended sediment, textural analysis, Cartagena Bay, fluvial discharge*.

INTRODUCTION

The Bay of Cartagena is located in the Caribbean Sea, off northwestern Colombia. The bay is of great historic, economic, and environmental importance. The city of Cartagena overlooks the bay and is the fifth largest city in Colombia, with ~1,200,000 inhabitants. It was founded in 1533, making it one of the oldest colonial cities in America and it is one of the most important tourist destinations in Latin America. Human occupation in the region has left a record of anthropogenic impacts. At present, the bay receives freshwater and sediment from the Canal del Dique, an artificial channel that connects the Magdalena River, the main waterway of the country, with the bay (Figure 1). The canal was built during the Spanish colonial period to connect Cartagena City directly with the interior of the country via the Magdalena River. Before the construction of the Canal del Dique, Cartagena Bay received no river inputs. The low concentration of suspended sediment and tropical seawater temperatures favored the presence of seagrass beds and coral reefs. The bottom of the bay was dominated by coarse carbonaceous sand, the weathering product of emerged reefs and coral terraces (Burel and Vernette, 1981; Leble and Cuignon, 1987; Martinez *et al*., 2010). The construction of the Canal del Dique changed the bay significantly, turning it into an estuarine environment in which terrigenous sediments play a significant role (Andrade *et al*., 2004; Franco *et al*., 2013; Restrepo *et al*., 2014a). Channel modifications through time have changed surface sediment deposition patterns in the bay and caused potential impacts on nearby ecosystems, such as Rosario Islands Natural Park, located ~45 km SW of the bay (Cendales, Zea, and Diaz, 2002; Moreno-Madriñan *et al*., 2015; Restrepo *et al*., 2012), and caused great concern for the environmental health of the bay (Cendales, Zea, and Diaz, 2002; Restrepo *et al*., 2005).

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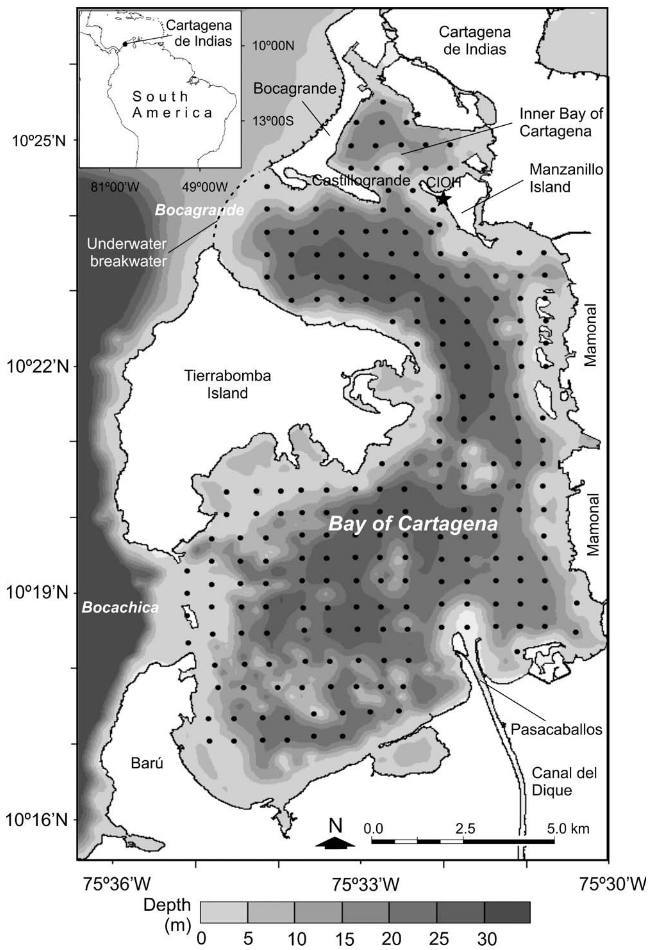

Figure 1. Bay of Cartagena map. Computational domain used in the MOHID model and sediment sample locations (black dots).

There have been several studies on the sedimentological and geomorphological characteristics of recent deposits in the Bay of Cartagena (Andrade *et al.*, 2004; Franco *et al.*, 2013; Klingebiel and Vernette, 1979; Leble and Cuignon, 1987; Restrepo *et al.*, 2014; Vernette, Lesueur, and Klingebiel, 1984). Studies show increasing predominance of terrigenous sediments in the bay, in agreement with the large influence of river inputs from the Canal del Dique, and an increase in sediment accumulation at sites within the bay and on the continental shelf. Textural and $CaCO_3$ analyses of surface marine sediments around the Rosario Islands Natural Park, along with satellite imagery analysis, show the expansion of terrigenous facies at the expense of carbonate facies, as a result of the progressive increase in continental inputs from the Canal del Dique (Leble and Cuignon, 1987; Moreno-Madriñan *et al.*, 2015). Bathymetric surveys conducted between 1935 and 2004 indicate that fine sediments transported by the Canal del Dique have covered sandy bottoms and advanced about 1 km north of the channel's delta (Andrade *et al.*, 2004). At present, turbidity currents and shallow marine deposits, both delivered by fluvial processes, are the two main types of recent deposits in the Bay of Cartagena (Franco *et al.*, 2013; Restrepo *et al.*, 2014). All previous studies agree that there has been a rapid decline of sand and $CaCO_3$ content in bottom sediments, particularly in the Canal del Dique prodelta, and that fine sediments of terrigenous origin predominate as a result of river inputs through the Canal del Dique (Andrade *et al.*, 2004; Franco *et al*, 2013; Restrepo *et al*, 2014a).

Recent studies suggest that the role of Colombian Caribbean rivers in the morphological stability of deltas, estuaries, and beaches, as well as bay sedimentation, increased as a result of greater river sediment inputs (Restrepo *et al.*, 2014b, 2015a,b). It has been estimated that all Colombian Caribbean rivers carry between 147 and 168×10^6 t y^{-1} of suspended sediment into the Caribbean Sea, with the Magdalena River accounting for 97% of this total sediment discharge (Restrepo and Kjerfve, 2004; Restrepo *et al*, 2015b.). Discharge variability depends mainly on climate conditions related to the migration of the Intertropical Convergence Zone (ITCZ) and El Niño–Southern Oscillation (ENSO) (Restrepo *et al.*, 2014b, 2015a,b). For example, high rates of suspended sediment transport (223×10^6 t y^{-1}) were recorded in the Magdalena River mouth between 2010 and 2012 as a result of severe flooding generated by the La Niña phenomenon (Restrepo *et al.*, 2015b). It has also been estimated that the annual rate of riverine suspended sediment transport has increased by 36% between 2000 and 2010 (Restrepo *et al.*, 2015b). Thus, it is possible that Cartagena Bay is experiencing increased sedimentation rates, greater abundance of fine sediments of terrigenous origin, and establishment of an estuarine environment as a result of increased sediment delivery from the Canal del Dique. Effects of the Canal del Dique discharge variability (seasonal changes related to the ITCZ and long-term changes associated with ENSO) on the bay's sedimentation processes and sediment distribution have not been studied.

In the last decade Cartagena has seen a significant increase in trade and port activities, with an increase of 138% in cargo moved by sea between 2000 and 2008, from 3.8×10^6 to 9.1×10^6 t y^{-1} (SPRC, 2009). It is important to determine whether the progradation of the Canal del Dique delta and sedimentation processes affect the Port of Cartagena access channel. There is a need to understand (1) changes in the composition and distribution of recent sediments in the bay and the relationship of such changes to riverine inputs, (2) the importance of river inputs from the Canal del Dique in sedimentation processes under different climatic–oceanographic scenarios, and (3) the role of coastal circulation patterns, including their variability, in sediment deposition processes.

This study explored patterns of coastal sediment movement and deposition under different seasonal conditions, *i.e.* warm and cold phases of the ENSO and normal conditions. This study also examined the spatial distribution of selected sediment characteristics (grain size, sorting, skewness, and kurtosis) in the Bay of Cartagena. The paper aimed to: (1) establish relationships between patterns of coastal circulation, sedimentation, and surface sediment distribution under different climate conditions (ENSO and normal conditions) and (2) determine the influence of the Canal de Dique input variability on the spatial distribution of bottom sediments and their textural characteristics.

Study Area

The Bay of Cartagena, Colombia, is located off northeastern South America (Figure 1). It is separated from the open Caribbean Sea by Tierrabomba Island. The bay is shallow, with a surface area of $\sim$82 km^2, and mean and maximum depths of 16 and 26 m, respectively. The bay is connected to the Caribbean Sea through the Bocagrande inlet in the north, and the Bocachica inlet in the south (Figure 1). The Bocagrande inlet is restricted by an underwater breakwater that was built during colonial times. Water depth in the Bocagrande inlet varies between 0.6 and 2.1 m. The Bocachica inlet reaches a maximum depth of 15.0 m (Figure 1). Tide in the Bay of Cartagena is mixed, but mainly diurnal, with a microtidal range that rarely exceeds 0.5 m (Molares, 2004).

The Bay of Cartagena and its surrounding areas are located in the Sinu fold belt. The belt is a 7-km-thick sequence of sandstones, claystones, and carbonate rocks of Miocene to present age. They are deposited in turbiditic to littoral environments on an accretionary prism whose morphological and stratigraphic evolution has been, in part, controlled by mud diapirism (Duque-Caro, 1984). Coastal hills defining the depressionary area of the bay have maximum heights of 120 m and are composed of claystones, sandstones, and reefal rocks aggregated in the Plio–Pleistocene-age La Popa formation (Duque-Caro, 1984). Differential coastal uplift associated with the effects of mud diapirism are conspicuous everywhere along the western and southern coasts of the bay (Tierrabomba and northern part of the Barú Peninsula), and are best expressed by several levels of tilted marine depositional and erosional terraces with a maximum height of 20 m (Duque-Caro, 1984; Martínez *et al*., 2010; Vernette, Lesueur and Klingebiel, 1984). The area of Mamonal (Figure 1) was made up of a series of sandstone and limestone hills with heights up to 70 m. Since 1970, limestone mining in the area led to the peneplanation of this coastal strip and the destruction of natural drains.

The main dry season in the region occurs from December to February. A weak rainy season occurs between March and May and there is a weak dry season between June and August. The main rainy season is from September to November (Mesa, Poveda, and Carvajal, 1997). During the dry season, NE trade winds predominate, with average speeds of up to 8.0 m s^{-1}. During the wet season, the intensity of these winds weakens, with average speeds of $<$3.0 m s^{-1}. Wind conditions, however, change during ENSO events. An El Niño event brings a decrease in wind speed from December to May, and an increase in wind speed from June to November. La Niña events result in the opposite effect (Ruiz and Bernal, 2009). Consequently, the warm and cold phases of ENSO may generate differential patterns of coastal circulation (*i.e*. Lonin and Giraldo, 1996, 1997; Rueda, Otero, and Pierini, 2013) and of the dispersion of the Canal del Dique turbidity plume within the bay (*i.e*. Lonin *et al*., 2004; Moreno-Madriñan *et al*., 2015).

Freshwater discharge from the Canal del Dique (Figure 1) has had a significant influence on the hydrology and sediment dynamics of the continental shelf and bay (Andrade *et al*., 2004; Leble and Cuignon, 1987; Lonin *et al*., 2004). Largest water and sediment discharges are recorded through the Canal del Dique mouth during November, reaching 800 m^3 s^{-1} and 31×10^3 t d^{-1}, respectively. Historical records indicate an average flow of 397 m^3 s^{-1} and a sediment transport rate of 5.9×10^6 t y^{-1} (Restrepo *et al*., 2005, 2014b). Colombian Caribbean rivers exhibit strong seasonal variability in flow, usually as high as 5–10-fold, comparing low to high monthly flow values (Restrepo and Kjerfve, 2004; Restrepo *et al*., 2014b). The Canal del Dique has high interannual river discharge variability, and carries a large proportion of its sediment load during relatively short time periods. Between 1984 and 1998 the channel transported $\sim 89 \times 10^6$ t of sediment into Barbacoas and Cartagena bays, about 50% of which was mobilized during only seven extreme events (Restrepo *et al*., 2005). Furthermore, ENSO has been identified as a second-order oscillatory component that influences hydrologic variability of the Colombian Caribbean rivers (Restrepo *et al*., 2014b, 2015a). Thus, the interannual variability associated with ENSO can be equal to the variability driven by ITCZ shifts. A factor of 2 to 4 is seen when comparing low to high annual streamflow/suspended sediment transport (Restrepo and Kjerfve, 2004; Restrepo *et al*., 2014b, 2015a).

METHODS

This section describes the MOHID modeling system (Martins *et al*., 2001) used to assess the spatial distribution of sediments transported by the Canal del Dique to the Bay of Cartagena. This section also describes the analysis of the 234 surface sediment samples collected from the Bay of Cartagena (Figure 1). Fieldwork was carried out between November and December 2009.

Implementation of Littoral Circulation Numerical Models

The MOHID modeling system (Martins *et al*., 2001) was used to assess the spatial distribution of sediments transported by the Canal del Dique to the Bay of Cartagena. MOHID's hydrodynamic module calculates and updates information based on the solution of the primitive Navier–Stokes equations in a three-dimensional (3D) space for incompressible fluids. A detailed description of the model is found in Martins *et al*. (2001).

The MOHID numerical model was configured in three dimensions. This numerical approach uses a 3D advection–diffusion equation to calculate the dispersion and transport of sediments in the water column, in which the vertical advection includes the sedimentation rate of the particles. Adsorption and desorption are considered reactive processes within the model. These involve both the particulate and dissolved phases of the substance (*i.e*. sediment particle) being simulated, in which the two layers tend to be in balance. This balance is taken into account in the model by equations proposed by Hayter and Pakala (1989). The model for the interaction processes at the water–sediment interface uses an approach known as "fluff layer." Both the deposition algorithm (Krone, 1962) and the erosion algorithm (Partheniades, 2009) are based on the assumption that deposition and erosion never occur simultaneously, *i.e*. a particle that reaches the bottom has a chance of staying there that varies between 0 and 1, because the shear stress oscillates between the upper limit for deposition and zero.

The bathymetry used in the implementation of the MOHID model was obtained by integrating available hydrographic survey charts of the Bay of Cartagena. Chart scales vary between 1:100,000 and 1:25,000 and cover the entire area of the Bay of Cartagena and its proximal continental shelf. These charts were made from bathymetric surveys conducted since 2005. The computational domain used by the numerical model is shown in Figure 1. The grid spacing implemented in Cartagena Bay was 50×50 m. The total number of grid points was 221×357 cells in a rectangular grid over the entire area of study. The 3D numerical model had a vertical discretization in Cartesian coordinates. The model had five defined layers with thicknesses of 2.0, 5.0, 5.0, 5.0, and 50.0 m, from the surface to the bottom.

The boundary conditions of sea level for the outer mesh were obtained by developing astronomical tide series using an interpolation method based on the model AG95.1 (Andersen, Woodworth. and Flather, 1995). Sea-level conditions are generated for each of the nodes located along the open boundary. Sea-level conditions are loaded into the model with a 15-minute temporal resolution format. Wind data were acquired from daily means from the QuikSCAT satellite. The database ran from 20 July 1999 to 22 November 2009, and includes data from this time period. Wind series were acquired from the node located at 10°15′ N, 75°45′ W.

The study considered three global climate scenarios to run the model: normal year (2006), ENSO-year warm phase (2002), and ENSO-year cold phase (2008). These scenarios were selected because of (1) the magnitude of the ENSO events during those years, (2) the consequent effect on the Canal de Dique discharge variability (*i.e*. Restrepo *et al*., 2014), and (3) the availability of complete monthly records of suspended sediment flow and suspended sediment load. In addition, recent studies show that during the dry season, the ENSO (warm or cold phase) event does not cause significant changes in wind direction in the Colombian Caribbean. Changes in wind direction are more pronounced, however, during the cold phase of ENSO in the wet season (Ruiz and Bernal, 2009). In the wet season, winds from the SW and north are more frequent. These winds are not present in the wet season during in a normal year or during the warm phase of ENSO (Ruiz and Bernal, 2009).

Wind roses for each of these years are shown in Figure 2. Additionally, the study accounted for regional seasonal climate scenarios, *i.e*. dry and wet seasons, driven by the annual movement of the ITCZ. The meteorological information required by the model, such as air temperature, atmospheric pressure, relative humidity, and solar radiation, were taken from the weather station located at the Centre for Oceanographic and Hydrographic Caribbean Research (CIOH). Monthly average water discharge values through the Canal del Dique to the Bay of Cartagena for normal years, the ENSO warm phase, and the ENSO cold phase are shown in Figure 3a.

Model parameters such as turbulence, wind drag coefficients, and bottom and contour friction coefficients for the bay were calibrated following Rueda, Otero, and Pierini (2013).This study used the model execution parameters and computational domain of Rueda, Otero, and Pierini (2013). The model defined

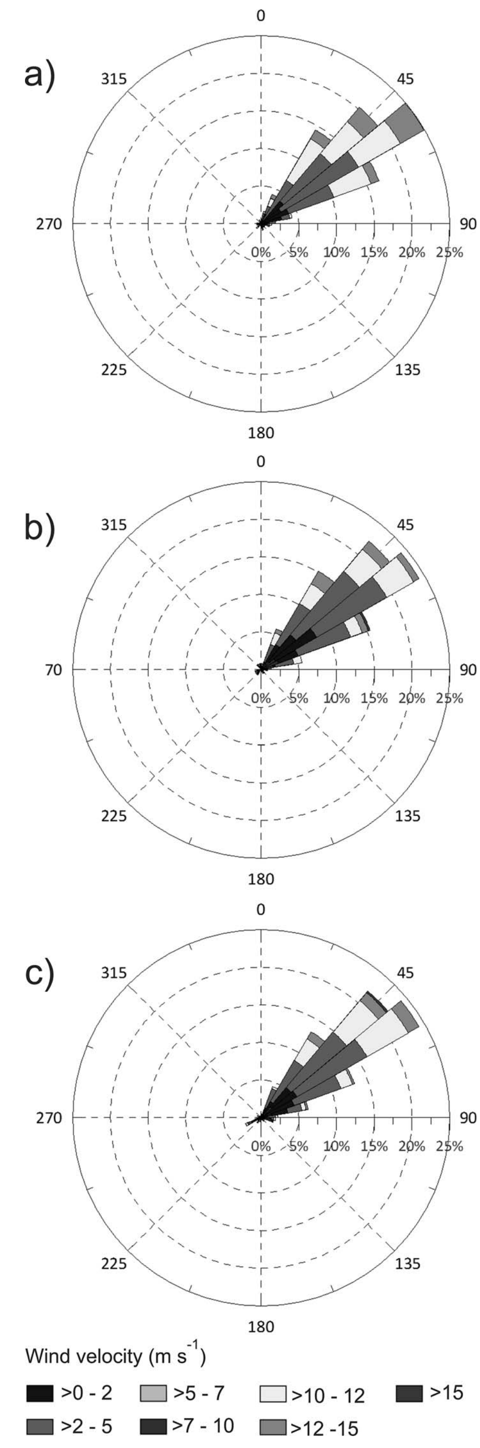

Figure 2. Daily average wind roses for the Bay of Cartagena: (a) 1998 (ENSO warm phase), (b) 2006 (non-ENSO conditions), and (c) 2008 (ENSO cold phase).

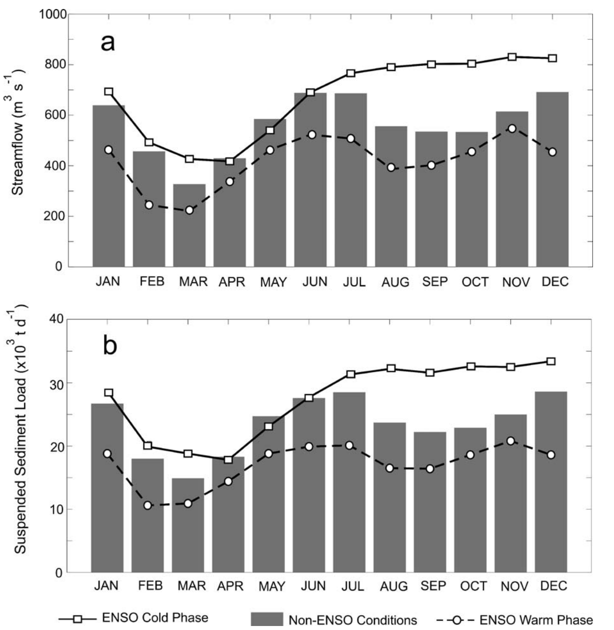

Figure 3. (a) Monthly average water discharge and (b) monthly average suspended sediment load from the Canal de Dique to the Bay of Cartagena in 2002 (ENSO warm phase), 2006 (normal conditions), and 2008 (ENSO cold phase). Data from Instituto de Hidrología, Meteorología y Estudios Ambientales de Colombia (IDEAM).

a time lapse of 9.8 seconds, a horizontal viscosity (K_H) of 0.001 $m^2 s^{-1}$, and a roughness coefficient of 0.0024.

Clays and silts dominate the particle discharge coming out of the Canal del Dique (Universidad Nacional, 2007). Total suspended sediment load curves along the Canal del Dique were obtained from available measurements and analyses of liquid and solid flows (National University, 2007). Suspended sediment load for a normal ENSO year, a warm ENSO phase, and a cold ENSO phase are shown in Figure 3b. The MOHID system assumes that the transport of cohesive sediment occurs only in suspension. Thus, transportation depends only on the advection–diffusion equation, with a settling velocity included in the vertical advection (Martins *et al*., 2001). The settling velocity W_s ($m\ s^{-1}$) is calculated, considering the effect of sediment concentration (C, $kg\ m^{-3}$) on flocculation and the hindered settling effect above a concentration ($\sim$20 $kg\ m^{-3}$), on the basis of the formulation proposed by Nicholson and O'Connor (1986). Models were configured to run through three consecutive months for each seasonal period (dry, transitional, and wet) and each potential ENSO phase (normal, warm, and cold).

Collection and Analysis of Surface Sediments

Two hundred thirty-four surface sediment samples from the Bay of Cartagena were collected in this study (Figure 1). Fieldwork was carried out between November and December 2009. Sediment samples were obtained with a Van Veen grab operated from a boat equipped with a Garmin GPS system with an accuracy of $\pm$5.0 m. Sample preparation to determine textural characterization included addition of 0.25 g of $(NaPO_3)_6$ to prevent particle flocculation and drying at 70°C for 24 hours. The grain size distribution of the coarse fraction ($\geq$63 μm) was determined by sample sieving, whereas the grain size distribution of particles $<$63 μm was determined by laser diffraction analysis using a Lumosed photosedimentator. This method uses Stokes' law in an aqueous medium (deionized water) to calculate grain size distribution curves. The method is also suitable for clay-size particles, as time measurements are shorter compared with other methods (Mittal, 2012; Partheniades, 2009). Texture analysis of the sediment samples was done with the GRADISTAT program (Blott and Kenneth, 2001), which uses the Folk and momentum measures (Folk and Ward, 1957) to calculate grain size parameters (*i.e*. mean, sorting, skewness, and kurtosis). This approach has been used by several authors to describe the properties of coastal sedimentary environments and their relationship with deltaic and estuarine processes (*e.g*., Alsharhan and El-Sammak, 2004; Cupul-Magaña *et al*., 2006; Franco *et al*., 2013; Minh-Duc *et al*., 2007; Restrepo *et al*., 2014a).

RESULTS

This section describes textural characterization and distributional patterns of surficial sediments and the circulation and sediment patterns in the Bay of Cartagena during different seasonal conditions, *i.e*. warm and cold phases of ENSO and normal conditions.

Textural Characterization and Distributional Patterns of Surficial Sediments

Surface sediment average grain size ranged between –0.54 φ and 6.43 φ, with a predominance of medium-size sediment (5.35 φ $\pm$ 1.2 φ). Only 11.5% of the samples were classified as sand or gravel (φ $<$ 4). Sediment sorting ranged from very poorly to well sorted, with a strong dominance of poorly sorted sediments (σ = 1.63 $\pm$ 0.8). Sediments showed remarkable symmetry (Sk = –0.052 $\pm$ 0.2), with only 27 samples skewed to the coarse size and seven samples skewed to the fine size. Most sediment is classified as very leptokurtic and platykurtic, with a mean kurtosis (k) of 0.84 $\pm$ 0.4 (Figure 4).

Average grain size and sediment sorting show an inverse relationship, useful to identify three associations. The first association is composed of poorly sorted medium-size sands to gravel (0 $<$ φ $<$ 2). A second group is composed of poorly sorted fine-size sands to coarse-size mud (2 $<$ φ $<$ 5). The third association, which includes the majority of samples, is composed of poorly sorted medium-size mud (5 $<$ φ $<$ 6) (Figure 4a). The relation between skewness and kurtosis is concentrated toward average asymmetry values, with most of the samples classified as symmetric with a kurtosis ranging from platykurtic to mesokurtic (Figure 4b). The relation between asymmetry and sorting showed two main groups. Most samples are classified as symmetric and poorly sorted, with a second group composed of sediments that are very poorly sorted, asymmetric, and skewed toward the coarse size. A small set of samples ($<$3%) is composed of sediments that are poorly sorted with a tendency to fine-size grains (Figure 4c).

Textural parameters and sand percentages from each sample were analyzed through spatial interpolation (kriging drift) to determine patterns of surface sediment distribution in the Bay

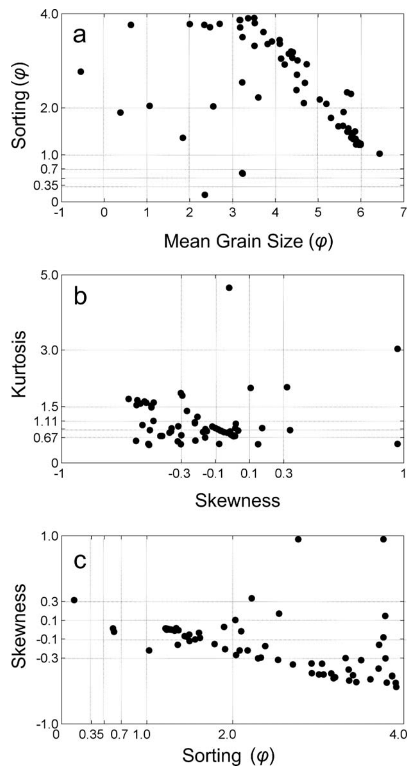

Figure 4. Bivariate figure between (a) mean grain selection and size, (b) skewness and kurtosis, and (c) selection and asymmetry. Modified from Restrepo *et al*., 2014.

of Cartagena (Figures 5 and 6). Samples with sand concentrations greater than 60% are located in the south-central to eastern area of the island of Tierrabomba, to the north of Mamonal, to the south of Bocagrande's breakwater, and in Bocachica and Manzanillo (Figure 6). These areas are also characterized by sediments that are very poorly sorted, and skewed to coarse-size grains (Figures 5b and c). In the Canal del Dique prodelta and the Coquitos coastal swamp there are symmetrical, mesokurtic, poorly sorted sediments with intermediate sand content (25–50%) (Figures 5 and 6). The Bay of Cartagena is, however, dominated by silt and clay grains, poorly selected, symmetrical, and mesokurtic (Figure 5). Sediments with the lowest sand content (<5%) are located along a latitudinal N-S axis from the Canal del Dique prodelta to the eastern end of the island of Tierrabomba, and in the central and northern part of the bay (Figures 5a and 6). Along this latitudinal axis, in the deepest areas of the bay, there are sediment deposition clusters with poorly sorted material that contains symmetric to coarse-size grains and is platykurtic (Figure 5). The inner bay, with the exception of the area north of the island of Manzanillo, is dominated by poorly sorted, symmetrical, and mesokurtic fine material (Figure 5).

Circulation and Sedimentation Patterns in the Bay of Cartagena

There are no changes in circulation patterns in the bay during the dry season for each ENSO phase (normal, warm, and cold). On the surface, currents move predominantly to the SW across the bay. Highest current intensities within the bay are on the west side of the Canal del Dique mouth, with values between 0.2 and 0.35 m s^{-1} (Figure 7). Water enters the bay through the Bocagrande inlet on the north side of the bay, and exits through the Bocachica and Varadero inlets in the SW area of the bay. Water currents during this dry season are mainly governed by the prevailing wind regime. The contribution of the tidal field to water currents is not significant because of their microtidal regime. Water from the Canal del Dique reduces its speed when entering the bay, and connects to the current that runs along the coast in the southern part of the bay. Both phases of ENSO (warm and cold) influence the magnitude of residual surface currents. Magnitudes of residual surface currents register a slight decrease during the warm phase of ENSO, especially in the central and SW sectors of the bay. A slight increase occurs in residual surface currents along the bay's coastline. Current magnitudes during the cold phase of ENSO are very similar to those recorded during a normal year for the dry season (Figure 7).

Circulation patterns during the wet season in the Bay of Cartagena vary for each ENSO phase (Figure 7). These changes occur especially in the north side of the bay. During the warm ENSO phase currents have a greater intensity with respect to both normal and cold phases (Figure 7e). The direction of surface residual currents is, however, the same in all three ENSO phases (cold, warm, and normal). Currents have a westward direction in the south bay area and a northwestward direction in the north and central sector of Cartagena Bay. In the northern part of the bay, surface residual currents are less intense. Surface residual net flow moves out of the bay through both the Bocachica and Bocagrande inlets during the wet season. This result is consistent with season dynamics when the greatest suspended sediments and freshwater contributions and suspended sediments are recorded through the Canal del Dique. Thus the ENSO cycle mainly affects current intensity during the rainy season.

The distribution patterns of sediments coming out of the Canal del Dique are influenced by seasonality and ENSO conditions (Figures 8). Highest sediment deposition is recorded in the outer part of the Canal del Dique mouth because of flocculation of cohesive sediments and reduction of the current's horizontal velocity. Sediments tend to settle in the southern region of the bay during the dry season. Sediments are transported mostly by the net residual current along the coast in this area of the bay. The fraction of sediment that remains in suspension is redistributed to the central and SW sector of the bay. Highest deposition of sediment occurs during the dry season in an ENSO cold phase (Figure 8c). The opposite occurs during a warm ENSO phase (Figure 8b). This pattern is strongly related to suspended sediments coming from the Canal del Dique, as shown in Figures 3a and b.

During the wet season, deposited sediment covers virtually the entire Bay of Cartagena (Figure 8) in all three ENSO phases (warm, cold, and normal). This pattern occurs because (1) during the wet season the largest discharge from the Canal del Dique enters the Bay of Cartagena, (2) residual surface currents move from the NE to the west on the central and north

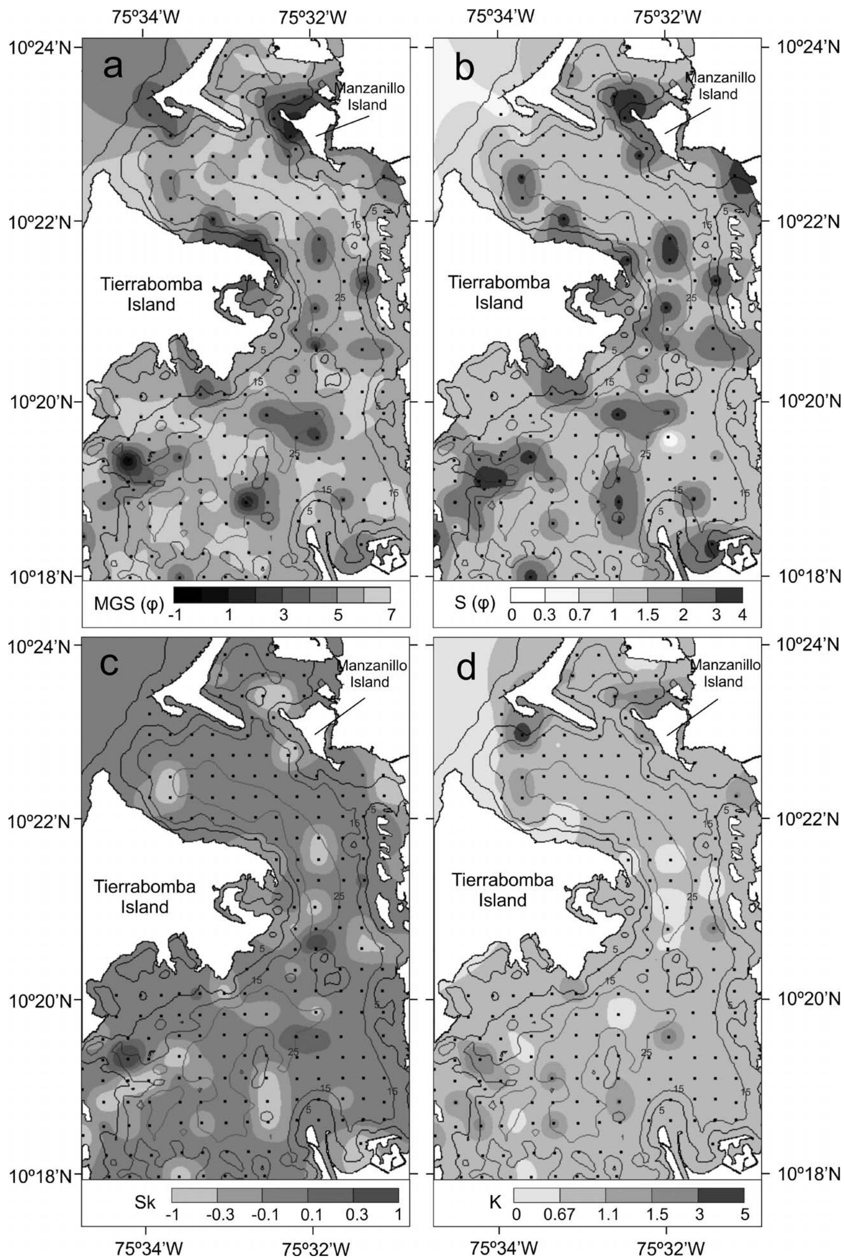

Figure 5. Spatial distribution of (a) mean grain size (MGS), (b) sorting (S), (c) skewness (Sk), and (d) kurtosis (*k*). Thin lines represent depth contours of 5, 15, and 25 m. Modified from Restrepo *et al.*, 2014.

areas of the bay, and (3) winds from the SW are more frequent, sometimes generating intense S-to-N currents that are able to transport sediments to the north side of the bay. The ENSO event affects the distribution of sediments on the bottom of the bay. The highest concentration occurs during the cold phase of ENSO (Figure 8f). This is a consequence of the magnitude of river inputs from the Canal del Dique. However, it is important to note that during the wet season, regardless of the ENSO phase, sediments carried by the Canal del Dique deposit over the entire Bay of Cartagena, and reach the Bocagrande beaches outside of the bay (Figure 8).

During the wet season and under the three ENSO phases (cold, warm, and normal) a residual surface current flows from the NE to the west. This surface current starts at the mouth of the Canal del Dique and connects the central area with the north side of the bay. This current transports sediments to the north side of the bay that are later transported by a net current that flows from the central part of the bay toward the inner Bay of Cartagena and Bocagrande opening (Figure 8f).

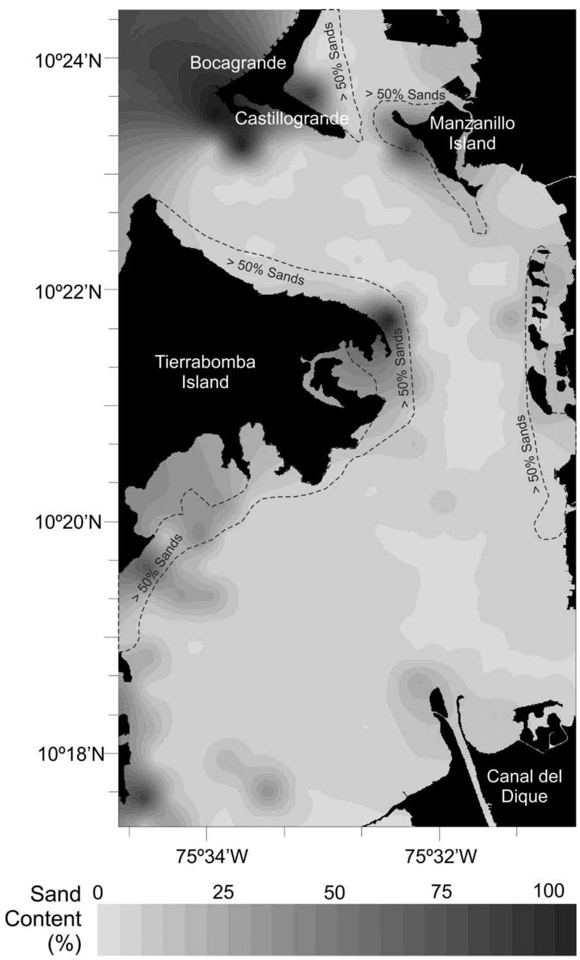

Figure 6. Spatial distribution of sand content (%) in surface sediments of the Bay of Cartagena. Black dotted lines indicate specific sand contents (%) reported by Pagliardini et al. (1982). Modified from Restrepo *et al*., 2014.

DISCUSSION

This section establishes relationships between patterns of coastal sediment movement and deposition, and the occurrence of the ENSO. There is an analysis of the influence of the Canal de Dique and coastal circulation patterns on the spatial distribution of bottom sediments and their textural characteristics.

Links between Circulation/Sedimentation Patterns and Sediment Properties

Water and sediment movements in the Bay of Cartagena are controlled mainly by the wind regime, salinity stratification caused by the flow of freshwater from the Canal del Dique, and variations in sea level, *i.e*. the microtidal range (Lonin and Giraldo, 1996, 1997; Rueda, Otero, and Pierini, 2013). During the dry season (December to April) the Canal del Dique registers its lowest flows ($\sim$180 m^3 s^{-1}) and stable northeasterly winds (trade winds), with speeds of $\sim$8 m s^{-1}. During normal conditions (April–July) the Canal del Dique discharge increases slightly ($\sim$250 m^3 s^{-1}) and experiences less intense winds ($\sim$ 5 m s^{-1}) that blow across the Bay of Cartagena from several directions (N, NE, E, and SE). Although the Canal del Dique discharge increases significantly ($>$400 m^3 s^{-1}) during the wet season (August–November), the winds at that time are weak and blow across the Bay of Cartagena mainly from the SW (Lonin and Giraldo, 1996; Molares, 2004; Ruíz and Bernal, 2009). In summary, the dry season is characterized by low discharge from the Canal del Dique and strong winds, whereas the wet season is defined by high river discharge and light winds. As a result of these hydrodynamic conditions, the Bay of Cartagena has been classified as a system of moderate to low energy (Restrepo and López, 2008; Rueda, Otero, and Pierini, 2013). Moreover, its submarine morphology (Figure 9) restricts exchange of water with the open Caribbean Sea and contributes to the dissipation of incoming waves (Lonin *et al*., 2004; Molares, 2004).

Conditions of moderate to low energy and the seasonal variability in the circulation patterns of the bay have led to differences in the spatial distribution of surface sediments (Figure 5) and created a sedimentary environment characterized by poor sorting of the material (Figure 4). The hydrodynamic model identifies three circulation patterns in the Bay of Cartagena. During the dry season there are two currents with magnitudes of 0.1 to 0.2 m s^{-1} that flow in a N-to-S direction along the coasts of Tierrabomba and Mamonal islands. There is also a countercurrent in the central part of the bay that flows in a S-N direction at speeds of $>$0.05 m s^{-1} (Figure 7). In contrast, during the wet season, the counterflow current reaches the inner bay and the area of Bocagrande with persistent, but weaker, velocities ($<$0.05 m s^{-1}). During this season the two coastal currents are also considerably weaker (Figure 7).

For the simulated climate years, circulation patterns did not change during the dry season. During the warm phase of ENSO of the dry season, the magnitude of the current increases in the Bay of Cartagena. In the wet season, currents are more intense during the warm phase of ENSO; whereas during the cold phase of ENSO, the intensity of these currents decreases. Currents in the Bay of Cartagena are controlled primarily by the magnitude and direction of the wind (Lonin and Giraldo, 1996; Lonin *et al*., 2004; Rueda, Otero, and Pierini, 2013). Therefore, during the cold phase of ENSO, the intensity and frequency of the trade winds increases, particularly in the dry season (Amador, 2008; Ruiz and Bernal, 2009), and there is a significant reduction in the residual current that flows from north to south. The ENSO phenomenon also modifies the patterns of residual currents during the wet season, especially in the northern part of the Bay of Cartagena. During the warm phase of ENSO, net flow occurs from the inner bay and Bocagrande toward the central sector of the Bay of Cartagena. During the cold phase of ENSO, this current reverses direction, *i.e*. it flows toward the inner bay and Bocagrande.

Sediment dispersion modeling shows that during the dry season, sediment deposition is focused in the south bay sector (Figure 8). Most of the sediment carried by the Canal del Dique sinks close to the mouth of the channel once it interacts with the waters of the Bay of Cartagena. This is a consequence of flocculation processes, loss of buoyancy, and a reduction in the strength of the currents. During the wet season, when river inputs from the Canal del Dique increase, sediments are

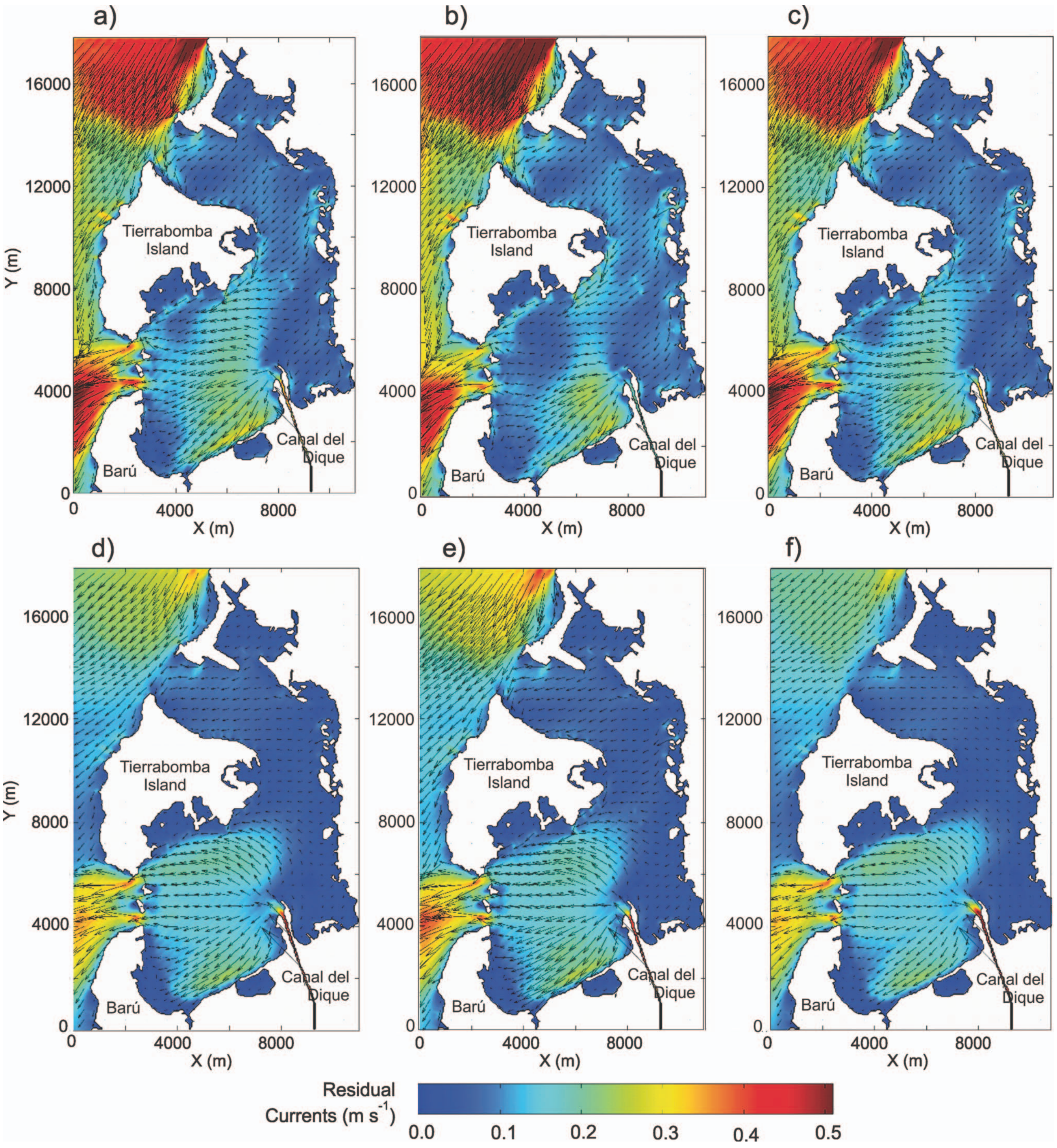

Figure 7. Residual surface currents fields in the Bay of Cartagena during the dry season for (a) normal year, (b) ENSO warm phase, (c) ENSO cold phase; and wet season for (d) normal year, (e) ENSO warm phase, (f) ENSO cold phase.

deposited across nearly the entire bottom of the Bay of Cartagena (Figure 8). During the cold phase of ENSO, sediment deposition reaches the inner Bay of Cartagena and the Strait of Bocagrande. This is mainly a consequence of the emergence of a net flow that begins at the mouth of the Canal del Dique and connects with coastal backflow compensation currents and with the current that flows from the center of the bay toward Bocagrande and the inner Bay of Cartagena (Figure 8f).

Circulation patterns and simulated sedimentation (Figures 7 and 8) show correspondence with the properties of the

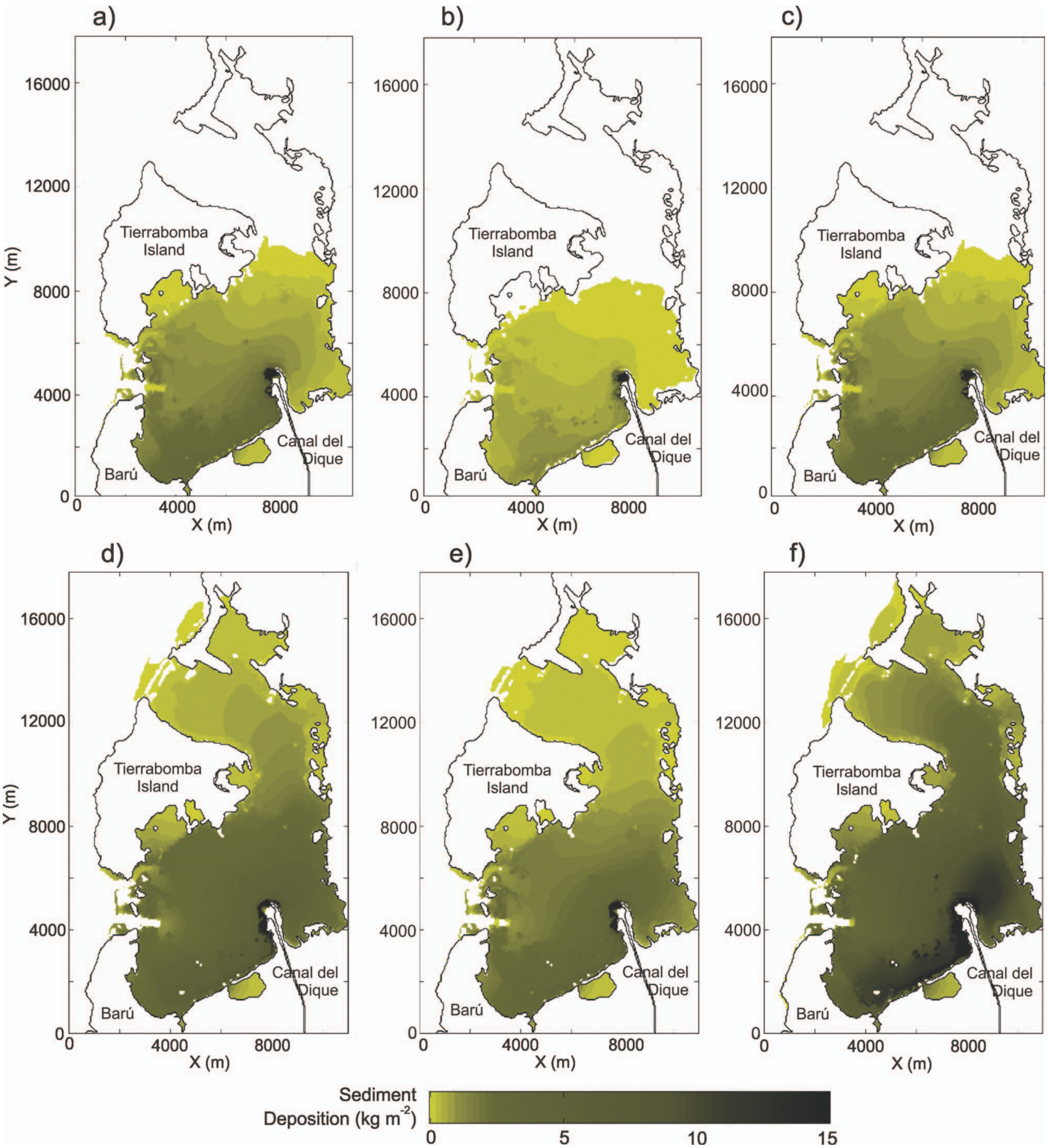

Figure 8. Distribution of deposited sediments coming out of the Canal del Dique during the dry season for (a) a normal year, (b) ENSO warm phase, (c) ENSO cold phase; and during the wet season for (d) a normal year, (e) ENSO warm phase, (f) ENSO cold phase. Concentration units for deposited sediments are in kilograms per square meter. The scale is limited to 15 kg m^{-2} to better illustrate distribution patterns in the figure. Total modeling time lapse for each season was 4 mo.

sediment collected at the bottom of the bay (Figure 5). Sediment parameters, particularly average grain size, depend on the dominant oceanographic/fluvial processes and bottom morphology of the bay. Whereas the distribution and spatial variability of sediment properties are related to the energy of transport (amplitude and variability), submarine morphology regulates the mass flows of water and energy. Sediments of Cartagena Bay are mainly composed of

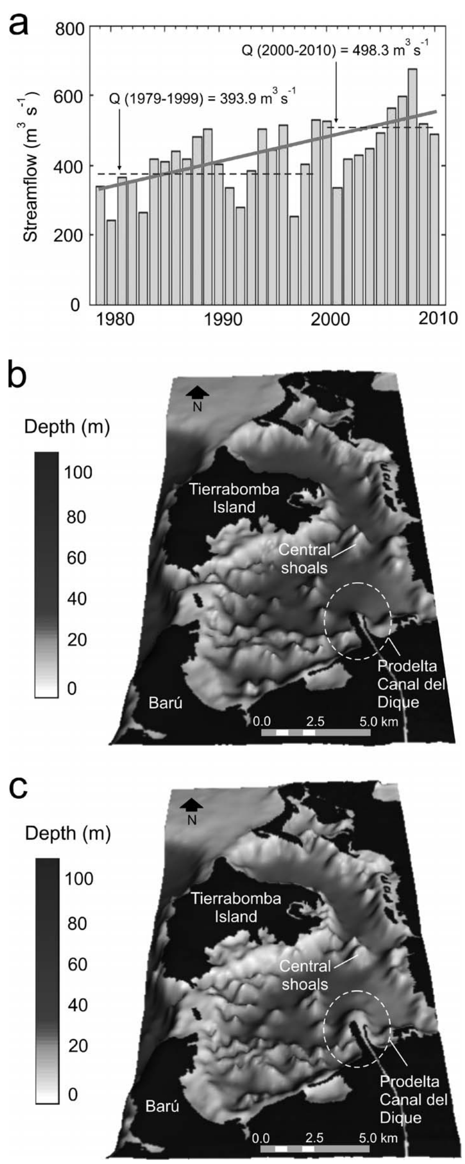

Figure 9. (a) Average monthly flows from the Canal del Dique (Station Santa. Helena, 1979–2010). The gray bold line represents the annual trend. Digital terrain models produced from bathymetric information on 1997 (b) and 2009 (c). The dotted white circle highlights the area of influence of the Canal del Dique prodelta. Modified from Restrepo *et al*., 2014.

poorly sorted lithoclastic mud, with a mostly symmetrical and mesokurtic to platykurtic distribution of grain size (Figures 4 and 5). Other representative groups are (1) coarse sands and biolithoclastic muds asymmetric to the fine grain size and (2) medium-size sands and bioclastic gravels asymmetric to the coarse grain size (Figure 4 and 5). These two groups have poorly sorted and leptokurtic to platykurtic grain size distributions. They are located in the area adjacent to the central and SE coast of Tierrabomba Island, Manzanillo Island, and the central banks of the Bay of Cartagena (Figure 5). Circulation patterns reveal that intense and variable coastal edge currents have contributed to the consolidation of poorly sorted gravels and sands in a strip near the islands of Tierrabomba and Manzanillo, the area north of Mamonal, and Bocachica sector (Figures 5, 7, and 8). These deposits come from the weathered Quaternary terraces located in these areas (*e.g.*, Martínez *et al*., 2010). On the other hand, the water and sediment flow controlled by the Canal del Dique discharge, running from the south to the north of the bay, has favored the transport and deposition of poorly sorted, symmetric, and mesokurtic mud in most of the Bay of Cartagena (Figures 5, 7, and 8). Sediments transported over relatively long distances are better sorted than those experiencing *in situ* weathering processes (Alsharhan and El-Sammak, 2004; Cupul-Magaña *et al*.,. 2006; Minh-Duc *et al*., 2007; Sahu, 1964; Shepard, 1963). In times of high river discharge, a northbound convective circulation occurs in the Bay of Cartagena. Freshwater from the Canal del Dique covers the entire bay with an average thickness of 15 m, reaching up to 22 m deep at the mouth of the Canal del Dique and 5 m in Bocachica (Cormagdalena, 2004). During these periods, the contribution of suspended solids from the Canal del Dique can reach 31×10^3 t d^{-1} (Restrepo *et al*., 2005). This combination of factors makes possible the transport and sorting of fine granular material into the Bay of Cartagena. During the dry and normal periods, the extent of the convective circulation decreases, and thus the backflow of the S-N current extends only to the middle area of the bay, but the Canal del Dique water and sediment discharge still play a role in determining surface sediment distribution patterns. Thus circulation and sedimentation patterns explain (1) the difference in sand content between shallow and deep areas of the bay, (2) the accelerated progression of terrigenous facies within the bay, and (3) the presence of fine sediments of terrigenous origin in the inner Bay of Cartagena, the farthest area from river influence.

Role of Canal del Dique in Shifting Sedimentation Patterns

Martinez *et al*. (2010) established that about 2.2 ka before present the Bay of Cartagena had surface sediments dominated by carbonate mudstones, with patchy reefs. Progradation of clastic origin began, however, as a consequence of a larger coastal dynamic (Burel and Vernette, 1981). Thirty years ago, Pagliardini *et al*. (1982) indicated that although the sediments of the Bay of Cartagena displayed a range of sizes, bioclastic calcareous sands dominated in areas of gentle slopes such as Bocagrande, Castillogrande, and the northern area of Tierrabomba (Figure 6). Pagliardini *et al*. (1982) also established that whereas muddy sediments covered a significant proportion of the bay, they did not constitute the dominant sediment type. Distribution of these muds was limited to deep zones protected by islets and came mainly from river inputs of the Magdalena River. The Magdalena River empties into the Caribbean Sea and is located 120 km NE of the Bay of Cartagena. Pagliardini *et al*. (1982) considered the effect of the Canal del Dique to be limited to very local sedimentation processes in the Bay of Cartagena. They argued that the canal had a relatively low flow rate (<100 m^3 s^{-1}) and most of its sediment load was deposited in the mouth of Pasacaballos. Subsequently, as a result of increased sediment input from the Canal del Dique and the formation of lateral bars (~1 km long at the mouth), the Bay of Cartagena changed from an estuarine to a deltaic system. It is now characterized by recent progression of terrigenous facies over carbonaceous and platform facies (Andrade *et al*., 2004). So far, no hydrosedimentological study in the Bay of Cartagena (Andrade *et al*, 2004; Klingebiel and Vernette, 1979; MITCH, 1973; Pagliardini *et al*, 1982; Vernette, Lesueur, and Klingebiel, 1984) has reported the presence of sands at the mouth of the Canal del Dique, and the progression of fine sediments to the southeastern part of the Tierrabomba Island sector and the internal bay, at the northern end of the Bay of Cartagena. As a result of the change in sedimentation patterns the fringe of carbonaceous sands that surrounds Tierrabomba Island has become narrower and the carbonate sediments that characterized the inner Bay of Cartagena are almost completely covered by mud.

Currently, the high content of fine-size sediments in the bay may be a consequence of contributions of suspended sediments from the platform, precipitation runoff, occurrence of mud diapirism, and river discharge through the Canal del Dique. Contributions from continental drift are limited by the Bocagrande breakwater and accumulate on beaches north of Bocagrande (Andrade, Arias, and Thomas, 1988). Precipitation is relatively low (<1200 mm y^{-1}) and sediment inputs from runoff are limited to the eastern part of the bay (Pagliardini *et al*., 1982). No study has reported mud diapirism in the Bay of Cartagena or geomorphological features associated with this process (Andrade *et al*. 2004; Klingebiel and Vernette, 1979; Martínez *et al*., 2010; Pagliardini *et al*, 1982; Vernette, Lesueur, and Klingebiel, 1984). Thus, river input from the Canal del Dique is the main cause for the increase in fine-size sediment content. This concurs with the increase in riverine input (36%) during recent years (Restrepo *et al*., 2014b, 2015a). Restrepo *et al*. (2014a) described a modern environment characterized by fluvial sedimentation in the Bay of Cartagena. According to the authors, this depositional environment explains the decline in grain size and the reduction in areas dominated by autogenous calcareous sediment (Figure 6).

Surface sediment distribution in the Bay of Cartagena is controlled by fluvial and morphological dynamics of the Canal del Dique delta. Other studies have obtained similar results (*i.e*. Franco *et al*., 2013; Moreno-Madriñan *et al*., 2015; Restrepo *et al.,* 2014a). The Canal del Dique has discharged into the Bay of Cartagena since 1924. The delta's subaquatic portion only began to form, however, at the end of the 1970s (Cormagdalena, 2004). The interaction between marine and fluvial environments has led to the formation of a mixed sedimentary environment with dominant riverine attributes (Restrepo *et al*., 2014a). Delta formation has been enhanced by the increase in riverine inputs to the bay (Restrepo *et al*., 2014b). Average monthly flow increased from 300 $m^3 s^{-1}$ in 1997 to about 600 $m^3 s^{-1}$ in 2010 (Figure 9a). As a result of these changes, the Canal del Dique prodelta expanded laterally ~1 km and spread ~3 km northward into the bay (Figures 9b and c). Furthermore, comparison of bathymetric data collected over a 74-year period (1935, 1977, and 2004), as well as radiocarbon dating on samples from the island of Tierrabomba, indicate sedimentation rates for the Bay of Cartagena ranging from 1.2 to 5.0 cm y^{-1} (Andrade *et al*., 2004; Cormagdalena, 2004; Martinez *et al*., 2010). These values suggest that mean water depth in the bay has declined by ~0.8 to 3.2 m since 1934 as a result of sedimentation, mainly induced by the Canal del Dique fluvial contributions.

CONCLUSIONS

Cartagena Bay's sedimentation processes have changed dramatically, particularly over the past 30 years. Previously, the bay was characterized by an autogenous sedimentation process, dominated by silts and bioclastic clays. This study showed that the accumulation of terrigenous facies is not isolated, but rather, a generalized process within the bay. As a consequence of this progression, Cartagena Bay is dominated by poorly sorted mud, with a symmetrical and mesokurtic–platykurtic grain size distribution.

The textural characteristics of the surface sediments of the Bay of Cartagena are determined primarily by the fluvial dynamics of the Canal del Dique and hydrodynamics in the bay. Low to moderate energy conditions and seasonal variability of the bay's circulation patterns have led to a sedimentary environment characterized by poorly sorted sediments. Coastal flows have contributed to the deposition of gravel and poorly graded sands. Northbound currents within the bay have favored the transport and deposition of fine, symmetrical, mesokurtic, and poorly selected sediments in most of the Bay of Cartagena.

The connection between the Canal del Dique and the Bay of Cartagena is critical in shaping the bay's sedimentation processes. Currently, the interaction between marine and freshwater environments has created a mixed sedimentary environment, dominated by riverine attributes. The interaction of depositional environments (with fluvial domain) has led to: (1) a reduction, since 1980, in the area dominated by autogenous calcareous sediments, now covered with fine sediments of terrigenous origin, transported by the Canal del Dique; (2) presence of sand at the mouth of the Canal del Dique; and (3) progression of fine sediments to the SE region of the island of Tierrabomba, and the internal Bay of Cartagena.

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