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Subtidal Inner Shelf Currents off Cartagena de Indias, Caribbean Coast of Colombia

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Subtidal inner shelf currents off Cartagena de Indias, Caribbean coast of Colombia

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[1] Seasonal trends in inner shelf subtidal circulation off the coast of Cartagena de Indias, Colombia, are examined through the analysis of current profiles, hydrographic, meteorological and satellite data collected from 1999 to 2002. During the dry season (December–April) the water column is well-mixed and along-shelf currents flow southwestward following the steady trade winds. In the rainy season (May–November) the water column experiences continuous events of stratification and the along-shelf currents flow northeastward, opposing the weak southwestward winds. In the dry season the along-shelf circulation is mostly driven by wind forcing, while in the rainy season, the circulation is set by an alongshore baroclinic pressure gradient. In the cross-shelf direction upwelling conditions are observed most of the year and geostrophic balance conditions are found. **Citation:** Maza, M., G. Voulgaris, and B. Subrahmanyam (2006), Subtidal inner shelf currents off Cartagena de Indias, Caribbean coast of Colombia, *Geophys. Res. Lett.*, *33*, L21606, doi:10.1029/2006GL027324.

1. Introduction

[2] Interest on inner shelf processes has increased during the last decades in recognition of this region as the interface between the coastline and deep waters where the majority of transport and dispersion of nutrients, freshwater, marine organism in larval stage, sediments, and pollutants take place [*Wright*, 1995]. The rapid development along the coastline in response to tourism, industrial fisheries, oil and gas operations, has led to a continuous environmental pressure in the Caribbean Sea [*Mooers and Maul*, 1998] that can influence and change the local ecosystem. To date, the information available on circulation in the region is limited to the outer shelf and deep sea. Inner-shelf dynamics has received little attention and no in-situ measurements are available. In this paper, Acoustic Doppler Current Profiler (ADCP) data collected in the inner shelf off the Colombian coast near Cartagena de Indias in the Caribbean Sea, are presented. These data are combined with in-situ hydrographic, meteorological, and satellite observations to describe the seasonal variability of the subtidal circulation. Also, the response of the system to forcing changes is examined through a simplified momentum balance analysis.

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2. Data Availability

[3] The data collection took place on the inner shelf off the cape of Punta Canoas, on the Caribbean coast of Colombia (Figure 1). Time-series of currents were collected every 15 minutes using a 1200 kHz ADCP that was deployed at 19.50 m of water depth from November 1999 to August 2002. Currents were collected at 4 elevations corresponding to 5.5, 8.5, 11.5, and 14.5 m above the sea bed (Hawsen and Sawyer, P. C., unpublished report, 2003). The current records were hourly-averaged prior to further analysis. Near that location and for the period November 1999 to August 2000, an array of 5 Seabird SBE thermistors recorded sea water temperature at 5 elevations (2.6, 5.4, 8, 11.2 and 14.5 m) above the bed. In-situ hourly surface wind data (speed and direction) measured at 10 m above ground was obtained from a meteorological station nearby (see Figure 1). Both current and wind time-series were low-pass filtered to remove oscillations with periods shorter than 36 hours. In addition daily mean surface wind fields from QuikScat (Level 2B) are used. These are arranged on a $0.5^\circ \times 0.5^\circ$ grid generated by IFREMER-CERSAT, based on data distributed by JPL/PODAAC. Also sea surface height anomalies (SSHA) are utilized in this study as provided in the $1^\circ \times 1^\circ$ 10-day cycle gridded product of the GADGET database [*Snaith*, 2000]. The nearshore points selected are shown as 1A and 1B in Figure 1, while the offshore points are located 155 km offshore from the nearshore points (not shown). Additional data include 207 hydrographic casts collected during the period 1997 to 1998 at various locations in the vicinity of the ADCP deployment site.

3. Results and Discussion

[4] Two main climatic periods can be identified during the year: (i) dry and (ii) rainy seasons. The dry season extends from December to April and is characterized by low precipitation and predominance of the Trade winds that blow from the north/northeast. The rainy season covers the period May–November; it has the highest precipitation (average precipitation of 125.7 mm, Figure 2b); the winds are relatively weak and directed from north to south until August. Later on, the winds turn southwestward, especially during August – November. This climatic seasonality is typical of the southern part of the Caribbean Sea and is caused by the oscillations of the Inter Tropical Convergence Zone (ITCZ).

3.1. Wind Forcing

[5] QuikScat data from two locations (2A and 2B; see Figure 1) were compared with the daily-averaged values of the low-passed, in-situ collected data along the period

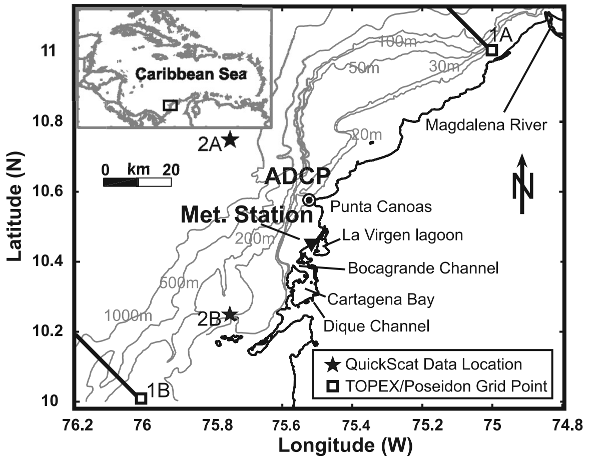

Figure 1. Study area showing instrument deployment sites, locations of buoyancy fluxes, points of QuickScat and TOPEX/Poseidon data utilized and transect locations used to carry out momentum balance analyses (for details see text).

1999–2002. The analysis showed that wind speeds were highly correlated (R = 0.77 and 0.79, for stations 2A and 2B, respectively) along the meridional and adequate correlated (R = 0.53 and 0.54) along the zonal components. The magnitudes of the in situ collected wind speeds were approximately 81% smaller than those obtained offshore from QuikScat, due to sheltering effect by the land. All wind data were rotated to an along- and cross-shelf coordinate system identical to that used for the currents (see section 3.4).

3.2. Buoyancy Fluxes

[6] The study area is seasonally influenced by the plume of the Magdalena River, located approximately 100 km to the north of the study site (Figure 1). Data from the period 1996–2000 (Figure 2c) show that river discharge is relatively low (5198 to 7106 m^3/s) from January to April (dry season); it gradually increases to 9048 m^3/s in July, then slightly reduces before maximum discharge (10,027 m^3/s) that occurs in November. Other minor sources of freshwater input include the Dique Channel which is located inside Cartagena Bay and releases its plume (2 to 3% of that of the Magdalena River) to the shelf through Bocagrande Channel (Figure 1) [*Cormagdalena–Universidad del Norte*, 1999]. During the rainy season, smaller buoyancy fluxes (∼34 m^3/s) enter the inner shelf through the lagoon of La Virgen [*Moor et al.*, 2002] and a network of streams located to the north of the lagoon with 5 year-return discharges between 35 and 100 m^3/s [*Universidad de Cartagena*, 1994].

3.3. Hydrography

[7] The analysis of the water temperature time series obtained from the thermistor array shows uniform bottom and surface temperatures for most of the dry season (January to April). However, temperature differences up to 1.5°C (averaged difference 0.75°C) are observed in the period May – August (rainy season) (Figure 2d). The same temperature structure was also observed in the analysis of the available CTD profiles. Furthermore, it was found that the water column is well-mixed during the dry season while episodes of stratification are evident during the rainy season.

3.4. Circulation

[8] The collected current data were rotated from a geographical to an orthogonal system with the *x*-axis (alongshore direction) defined by the direction (33°N) of the principal axis of the depth-averaged currents, which is roughly aligned with the 20 m isobath. Positive longshore velocities indicate northeastward directed flow, while positive cross-shelf velocities indicate offshore directed currents.

[9] Along-shelf winds (Figure 3a) oscillate between −12 m/s during January – February to almost zero in September-October (total standard deviation of 3.8 m/s). On the other hand, cross-shelf wind velocities (Figure 3b) are consistently directed offshore with a mean speed of 4 m/s (standard deviation 2.2 m/s). The currents are almost rectilinear, as the standard deviation of the minor axis currents component is as low as 10% to 25% of that along the principal axis. No significant variation in the direction of the principal axes of the flow as a function of depth was found. The standard deviation of the currents decreases from 0.26 to 0.18 m/s with depth, which is consistent with the effect of bottom friction.

[10] Comparisons of the alongshore wind velocities and current time series (Figure 3) indicate that winds coming from the northeast drive southeastward (downcoast)

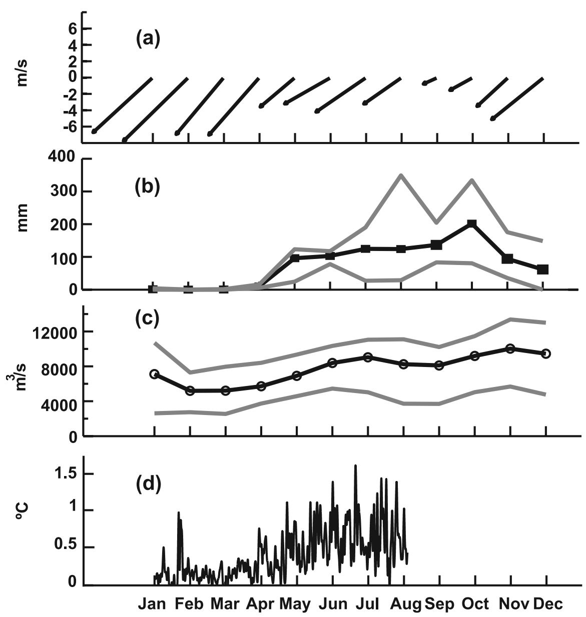

Figure 2. Multi-annual (1999–2002) monthly-averaged data. (a) Vectors of surface winds from QuikScat (grid point 2B); (b) maximum, mean and minimum accumulated precipitation; and (c) maximum, mean and minimum discharge of Magdalena river (1996–2000). (d) Difference in sea temperature between surface and bottom thermistors.

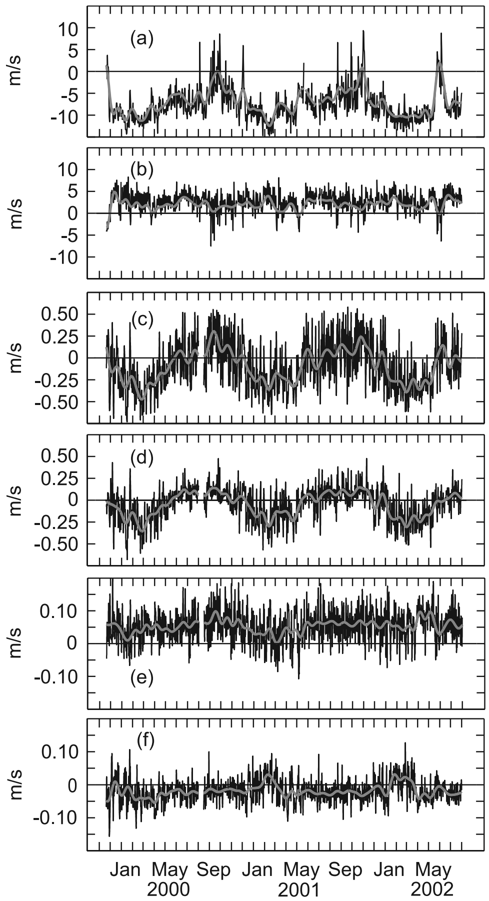

Figure 3. (a) Along-shelf and (b) cross-shelf components of surface wind velocities from QuikScat data in location 2B (see Figure 1). Along-shelf component of (c) near surface and (d) near the bottom current velocities. Cross-shelf component of (e) near surface and (f) near bottom current velocities. Gray bold lines represent low pass filtered time series with a cut-off period of 1 month.

currents in the period December–April (dry season). In the period May–November (rainy season), the currents follow a general northeastward direction with the maximum current speeds being related to periods of relaxation of the north/northeastern winds (Figures 3a, 3b, 3c and 3d). In the cross-shore, the predominant condition is persistent upwelling throughout the year with near bed onshore flows having smaller magnitude than the offshore surface transport leading to a net offshore mass flux at the study site (see Figures 3e and 3f). The depth-averaged value was removed from the cross-shelf velocities, and the near surface transport was calculated using the 2 upper bins. The low correlation coefficient between along-shelf wind stress and near surface transport (R = 0.04) suggests that the observed vertical structure of the cross-shelf circulation does not follow the pattern usually found on uniform shelves with a two-dimensional upwelling/downwelling response related to along-shelf wind stress action [*Lentz*, 2001].

3.5. Momentum Balance Analysis

[11] Assuming hydrostatic flow, small sea level variations compared with the water depth and neglecting wave radiation stresses and advective terms, the along-shelf and cross-shelf momentum balance terms can be written as:

$$\frac{\partial u}{\partial t} + fv = -\frac{1}{\rho_o}\frac{\partial P}{\partial x} + \frac{\tau^{sx}}{\rho_o h} - \frac{\tau^{bx}}{\rho_0 h} \quad (1)$$

$$\frac{\partial v}{\partial t} - fu = -\frac{1}{\rho_o}\frac{\partial P}{\partial y} + \frac{\tau^{sy}}{\rho_o h} - \frac{\tau^{by}}{\rho_0 h} \quad (2)$$

where (u, v) are the along- (x) and cross-shelf (y) sub-tidal, depth averaged components of velocity, h is the water depth, f is the Coriolis parameter, ρ_o is a reference density, $\partial P/\vartheta x$, $\partial P/\vartheta y$ are the depth averaged total (i.e., barotropic and baroclinic) horizontal pressure gradients, (τ^{sx}, τ^{sy}) are the wind stresses, and (τ^{bx}, τ^{by}) are the bottom stresses.

[12] The terms of equations (1) and (2) were estimated using the data available in this study. The local acceleration terms ($\vartheta u/\vartheta t$, $\vartheta v/\vartheta t$) were calculated based on the numerical differences between the current values. Bottom stress was estimated using a linear drag law as in the work by *Lentz and Winant* [1986] with a friction coefficient of $r = 5 \times 10^{-4}$ m/s. Wind stress was calculated using a neutral drag law [*Large and Pond*, 1981] and scatterometer winds from point 2-B.

[13] The cross-shelf pressure gradient was estimated along two cross-shelf sections located in the southern and northern parts of this study area originating at points 1A and 1B and extended 155 km offshore (see transects in Figure 1). These estimates are based on the 10-day cycle sea surface height anomalies from TOPEX/Poseidon. The rest of the terms were daily averaged for consistency in the comparisons with the wind stress term. The cross-shelf momentum balance shows that local acceleration and bottom stress (Figures 4a and 4e) are less important than the other three terms.

[14] It is characteristic that the low-passed Coriolis and pressure gradient terms (Figures 4b and 4c) although differ in magnitude by a factor of 2, exhibit a similar trend. They are both negative during the dry (December – April) and positive during the rainy season. On the other hand, the wind stress term is always positive throughout the year.

[15] In order to quantify the importance of the baroclinic contribution to the total cross-shelf pressure gradient term, hydrographic data (37 profiles collected during the period February – May 1998) from the vicinity of the ADCP deployment location were used. These data were combined with typical offshore density values obtained from *Cabrera and Donoso* [1993] and a typical cross-shore baroclinic pressure gradient term of -4.8×10^{-7} m/s^2 was estimated. The estimated value is two orders of magnitude smaller than the total pressure gradient term estimated from the satellite data (see Figure 4c) that fluctuates approximately between -0.9×10^{-5} m/s^2 and 0.77×10^{-5} m/s^2. This estimate indicates that the cross-shelf pressure gradient is predominantly barotropic.

[16] No direct estimates of the along-shelf pressure gradient can be obtained from the satellite data due to the fact that the sea level differences in this direction were too close to the range of error. However, using the momentum balance equation (1) with direct estimates of the other terms, a value for the pressure gradient term ($-1/\rho_o\ \partial P/\vartheta x$) was

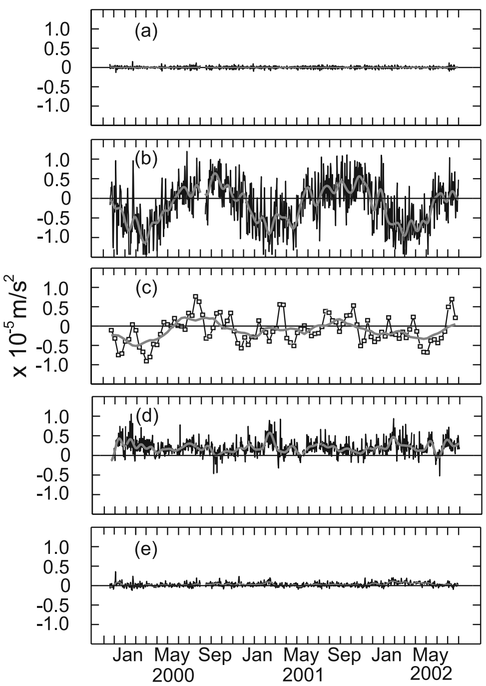

Figure 4. Comparison of cross-shelf momentum terms. (a) Acceleration ($\vartheta v/\vartheta t$); (b) Coriolis (*fu*); (c) pressure gradient ($-1/\rho_o\ \partial P/\vartheta y$); (d) wind stress ($\tau^{sy}/\rho_o h$) and (e) bottom stress ($-\tau^{by}/\rho_o h$) term. Gray bold lines represent low pass filtered time series with a cut-off period of 1 month.

estimated (see Figure 5c) that was found to be positive for most of the year. This implies that a negative total along-coast pressure gradient is present that can be caused either by baroclinic or by barotropic contributions due to decreasing density or decreasing sea surface elevation in the positive along-shelf direction (towards the northeast), respectively. This analysis shows that local acceleration (Figure 5a) and Coriolis (Figure 5b) are the smallest terms in the along-shelf direction. During December–May the wind stress is the most important term (Figure 5d) and is balanced by the bottom stress (Figure 5e) and pressure gradient, and as a result the currents follow the wind. During June–November the wind stress attains small values that in combination with the bottom stress, balance the dominant pressure gradient, and as a result the currents flow against the wind.

[17] The previous circulation and momentum balance analysis suggests that in the dry season the along-shelf circulation is mostly driven by wind forcing, while in the rainy season, the most important forcing factor is the estimated pressure gradient with an average value of 0.35×10^{-5} m/s^2. The origin of that pressure gradient can be attributed to differences in density in the shelf due to the dispersion of buoyant fluxes, and/or the interaction of the wind forced flow with the along-shore variations in shelf and coastline morphology. The possibility of a meaningful contribution of along-shelf variations in density to the generation of an along-shelf pressure gradient was examined by calculating the density variation needed to setup an alongshelf pressure gradient of the magnitude shown in Figure 5c. This was found to be -0.37 kg/m^3 in 20 km, which seems to be a reasonable value considering the dispersion of the buoyant fluxes from the sources described in section 3.2.

[18] At this juncture it should be noted that strong changes in the orientation of the coastline and the shelf of the area (i.e., in the vicinity of capes) can modify or accentuate the alongshelf pressure gradient via the barotropic component. In similar conditions of morphological variation as in our study, northward currents can develop in response to periods of relaxation of southward winds due to morphology induced pressure gradients. This has been shown numerically and experimentally for the Oregon coast by *Gan and Allen* [2002]. Pressure gradients were found to be generated in both sides of coastal capes by the along-shelf variations in the structure of along-shelf and cross-shelf flows. When the winds relax these pressure gradients generate currents opposing the winds. Similar processes have been linked to near shore current reversals observed in embayments along the east coast of the United States of America [*Gutierrez et al*, 2006]. Two facts are consistent with the presence of morphology-induced pressure gradients in the study area. First, the vertical structure of the cross-shelf circulation indicates that most of the year, no complete balance exists between near surface and near bottom cross-shelf transport. Secondly, the low correlation between along-shelf wind stress and cross-shelf transport suggests a three-dimensional structure of the cross-shelf circulation. Although, given the apparent dominance of the baroclinic component on the along-shelf pressure gra-

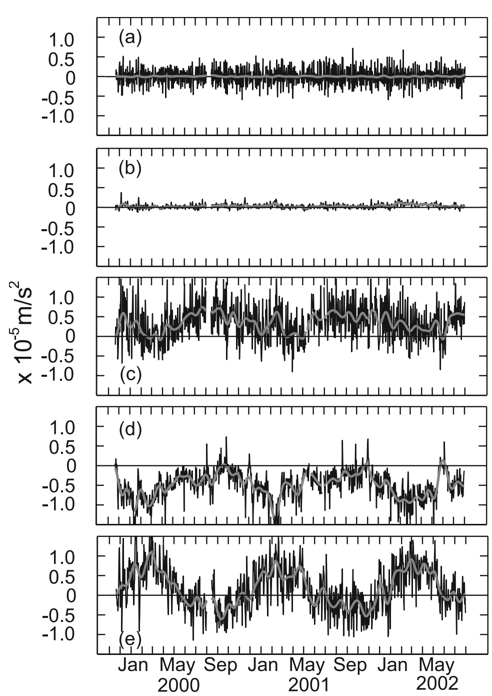

Figure 5. Comparison of along-shelf momentum terms. (a) Acceleration ($\vartheta u/\vartheta t$); (b) Coriolis (*fv*); (c) estimated pressure gradient ($-1/\rho_o\ \partial P/\vartheta x$); (d) wind stress ($\tau^{sx}/\rho_o h$); and (e) bottom stress ($-\tau^{bx}/\rho_o h$). Gray bold lines represent low-pass filtered time series with a cut-off period of 1 month.

dient term, a barotropic component influence can be present but it will play a secondary role.

[19] The dynamics driving the inner shelf currents is likely to be mostly of local origin. The possible links between the outer and inner shelf dynamics are the seasonal response to the temporal changes in wind stress and the geostrophic balance in the cross-shelf direction. The cross-shelf variability of the circulation and possible interactions of inner shelf and outer shelf processes require further investigation.

4. Conclusions

[20] The seasonal trends in the subtidal currents in the inner shelf off Cartagena de Indias are derived from analysis of ADCP, hydrographic, meteorological, and satellite data. The analysis reveals two main circulation features along the year. In the dry season (December–April) the circulation is characterized by strong along-shelf flows following the steady and strong trade winds from the north and northeast. In the rainy season (May–November) the currents reverse, opposing weak southwestward winds with regular episodes of relaxation. The alongshelf momentum balance analysis indicates that the currents respond mostly to the wind stress in the dry season and to the pressure gradient in the rainy season. In the cross-shelf direction the general trend along the year is upwelling, with near bottom transport reduced and the near surface transport enhanced, and the cross-shelf momentum analysis indicates a geostrophic balance.

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