

Evidence for an eastward flow along the Central and South American Caribbean Coast

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[1] Hydrographic transects suggest an eastward flow with a subsurface core along the entire southern boundary of the Caribbean Sea. The transport of the coastal limb of the Panama-Colombia Gyre (PCG), known as the Panama-Colombia Countercurrent, decreases toward the east (from ~ 6 Sv off Panama), as water is lost into the recirculation of the PCG. Off Panama, the flow is strongest at the surface, but, off Colombia, it is strongest at around 100 m. A portion of the counterflow (~ 1 Sv) continues eastward along the Colombian coast as far as the Guajira region (12°N , 72°W), where it submerges to become an undercurrent beneath the coastal upwelling center there. The eastward flow also occurs in the Venezuela Basin, beneath the coastal upwelling region off Cariaco Basin and exits the Caribbean through the Grenada Channel at around 200 m depth. Numerical simulations suggest that this flow, counter to the Caribbean Current, is a semi-continuous feature along the entire southern boundary of the Caribbean, and that it is associated with offshore cyclonic eddies. It probably constitutes part of the Sverdrup circulation of the Tropical North Atlantic cyclonic cell. *INDEX TERMS*: 4512 Oceanography: Physical: Currents; 4279 Oceanography: General: Upwelling and convergences; 4255 Oceanography: General: Numerical modeling; 4520 Oceanography: Physical: Eddies and mesoscale processes; *KEYWORDS*: undercurrents, ocean circulation, Caribbean Sea

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1. Introduction

[2] The Central and South American coast of the Caribbean Sea extends from the coast of Panama in the Gulf of Mosquitos in the west, to the Grenada Channel of the Lesser Antilles in the east (Figure 1). The southern boundary of the Caribbean Sea encompasses the continental shelves of Panama, Colombia and Venezuela. Beyond the shelf, the deep (>4000 m) Colombian and Venezuelan Basins are separated by the Beata Ridge, broken only at the Aruba Passage (>3000 m) north of the Guajira Peninsula. The smaller Grenada Basin lies further east, between the Aves Ridge and the Lesser Antilles.

[3] The dominant surface currents in the area are the Caribbean Current flowing west-northwestward through the northern Caribbean [e.g., *Wüst*, 1963; *Morrison and Nowlin*, 1982] and the cyclonic circulation of the Panama-Colombia Gyre (PCG) in the southwestern Caribbean Sea (SWCS) [*Mooers and Maul*, 1998; *Schott and Molinari*,

1996]. The limb of the gyre abutting the coast is known as the Panama-Colombia Countercurrent (PCC) [*Pujos et al.*, 1986]. Intense air-sea interaction through wind stress and surface heat flux forcing, Western boundary current throughflow, instabilities of the Caribbean Current, and freshwater input along the Central and South American coast drive these energetic and time-dependent flows. The surface circulation in the PCC has been documented extensively on the basis of drifter tracks [*Criales et al.*, 1999; *Wilson and Leaman*, 2000]. However, the subsurface structure of neither the PCC nor the Venezuela Countercurrent has been described, except for appearances in sporadic basin-wide sections [e.g., *Gordon*, 1967; *Hernandez-Guerra and Joyce*, 2000].

[4] There is theoretical evidence for the existence of an eastward flow in the southern limb of the Caribbean Sea based on both the remote North Atlantic circulation and the local wind-driven circulation. The Sverdrup climatological circulation has a zonal zero line in the center of the Caribbean [*Mayer and Weisberg*, 1993] corresponding to the presence of the Low Level Jet in the Trade wind regime around 14°N and implying existence of a cyclonic cell in

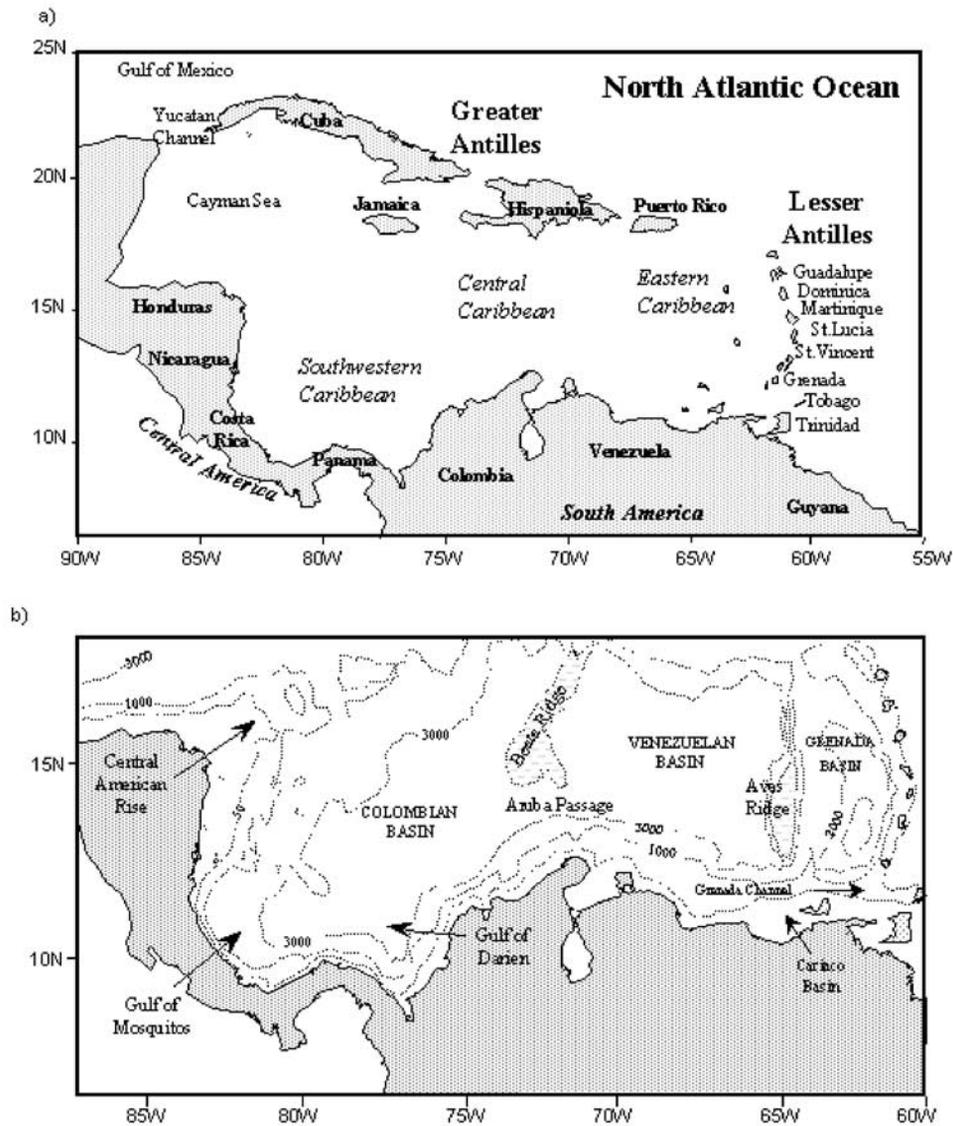


Figure 1. Caribbean Sea: (a) some geographical features and (b) some geomorphological features of the southern Caribbean.

the southeastern Caribbean (Figure 2). Closing the Tropical North Atlantic Sverdrup circulation requires a mean transport of approximately 5 Sv from the southern Caribbean, a transport that is likely offset to a large degree by the poleward transport of the upper ocean part of the North Atlantic thermohaline circulation.

[5] Wind stress of the Northern Trade winds is the primary forcing for the surface currents in the Caribbean. With the almost constant easterly zonal winds, Ekman transport is northward, producing divergence (coastal upwelling) from the South American coast and convergence (coastal downwelling) toward the Greater Antilles [Gordon, 1967]. Furthermore, the wind stress curl produces open ocean upwelling (downwelling) between the coastal areas and mid-basin. Thus a current system typical of a coastal upwelling circulation including a subthermocline-level countercurrent (a coastal undercurrent) may be expected. The westward wind stress, as well as producing coastal upwelling, can create a zonal pressure gradient with a

pressure head at the Central American coast that can contribute to driving the eastward flow. The expectation of a “locally” produced counterflow reinforced by the “remote” effect of the Sverdrup circulation cell suggests the hypothetical existence of an eastward flow along the South American Caribbean coast. This paper presents evidence for a counterflow along the South American continental margin from Panama to Venezuela. In particular, the structure and transport of the southern Caribbean currents at several locations along the coast are described on the basis of both in situ observations and model output to provide new insight into the little-documented circulation of this region.

2. Methodology

[6] Hydrographic data are utilized together with current measurements taken during the 1990s in the Colombian, Venezuelan, and Grenada Basins. The Colombian Basin

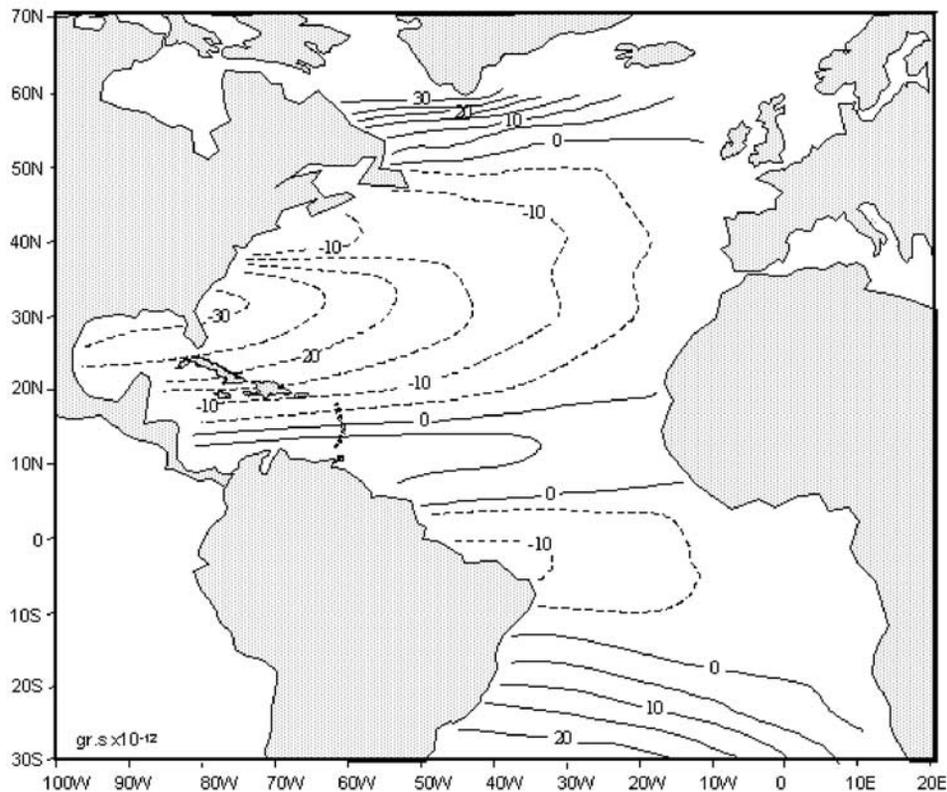


Figure 2. Average annual stream function field for total Sverdrup transport based on Comprehensive Ocean-Atmosphere Data Set (COADS) data from 1947 to 1988. The zero line divides the Caribbean in half. The cyclonic tropical cell in the North Atlantic implies about 5 Sv exiting the South American coast. Figure is reproduced from *Mayer and Weisberg* [1993], redrawn from *Wilson and Johns* [1997].

was surveyed during several cruises in 1994, 1997, and 1998 (Figure 3). Two CTD sections made by R/V *Providencia* in July 1997 sampled the Colombian Basin with a station separation of around 25 km. Field data in the Guajira region were obtained from three cruises during 14–22 April, 1994, 17–19 February, 1998, and 20–25 November, 1998, by R/V *Malpelo* (Figure 4). The cruises in the Guajira occurred during different tropical seasons: (1) the peak of the windy upwelling season (December–March), (2) the transition after the windy season (April–July), and (3) the rainy season of relaxed wind and weak or no upwelling (August–November) to observe possible seasonal changes. Maximum spacing between stations was about 50 km in the oceanic region and 5 km near the Guajira Peninsula. In all sections, stations were made perpendicular to the continental shelf so that transport calculations are good estimates of the alongshore coastal currents.

[7] In situ oceanic variables were observed with a Sea Bird CTD SB-19 probe to 1200 m or about 10 m above the seabed where shallower. The profilers were calibrated at the factory prior to each cruise. The CTD measurements were also checked against values obtained at one oceanographic control station made with twelve Nansen bottles at standard depths off Cartagena Bay at the beginning of each cruise. CTD data were compared with reversing thermometer temperatures and water bottle salinities were determined with a Beckman inductive salinometer. Mean differences of 0.03°C and 0.005 ppt, respectively, were considered suffi-

ciently small that it was unnecessary to make any correction to the data.

[8] Geostrophic calculations were made for each oceanic section referenced to 1200 dbar. The 1200-dbar surface was used as the reference level for geostrophic calculations, because it was the maximum depth in most stations, and has been used previously in the Caribbean Sea [*Gordon*, 1967; *Roemmich*, 1981]. We conclude it is an adequate reference level from examination of lowered ADCP data of *Joyce et al.* [2001], which show minimum speeds around that level. Where the depth was shallower than the reference level, as at stations close to the shore, the method used to determine the geostrophic velocity was the one proposed by *Reid and Mantyla* [1976]. The station spacing was great enough to estimate a significant baroclinic signal for the computations.

[9] ADCP data from R/V *Columbus Iselin* in March–April 1992 along 75°W [*Rooth*, 1992] provided direct measurement of the flow along the Colombian coast. Also, ADCP data from R/V *Knorr* in August 1997 along 66°W [*Hernandez-Guerra and Joyce*, 2000] were used to observe the coastal currents in the Venezuelan Basin. Finally, ADCP observations made from the HMBS *Trident* in May 1992 and the R/V *Malcolm Baldrige* in April 1994, along a transect between Grenada and Trinidad [*Wilson and Johns*, 1997] were examined for the fate of the coastal current at the southeasternmost corner of the Caribbean Sea where it communicates with the open Atlantic Ocean. The ADCP

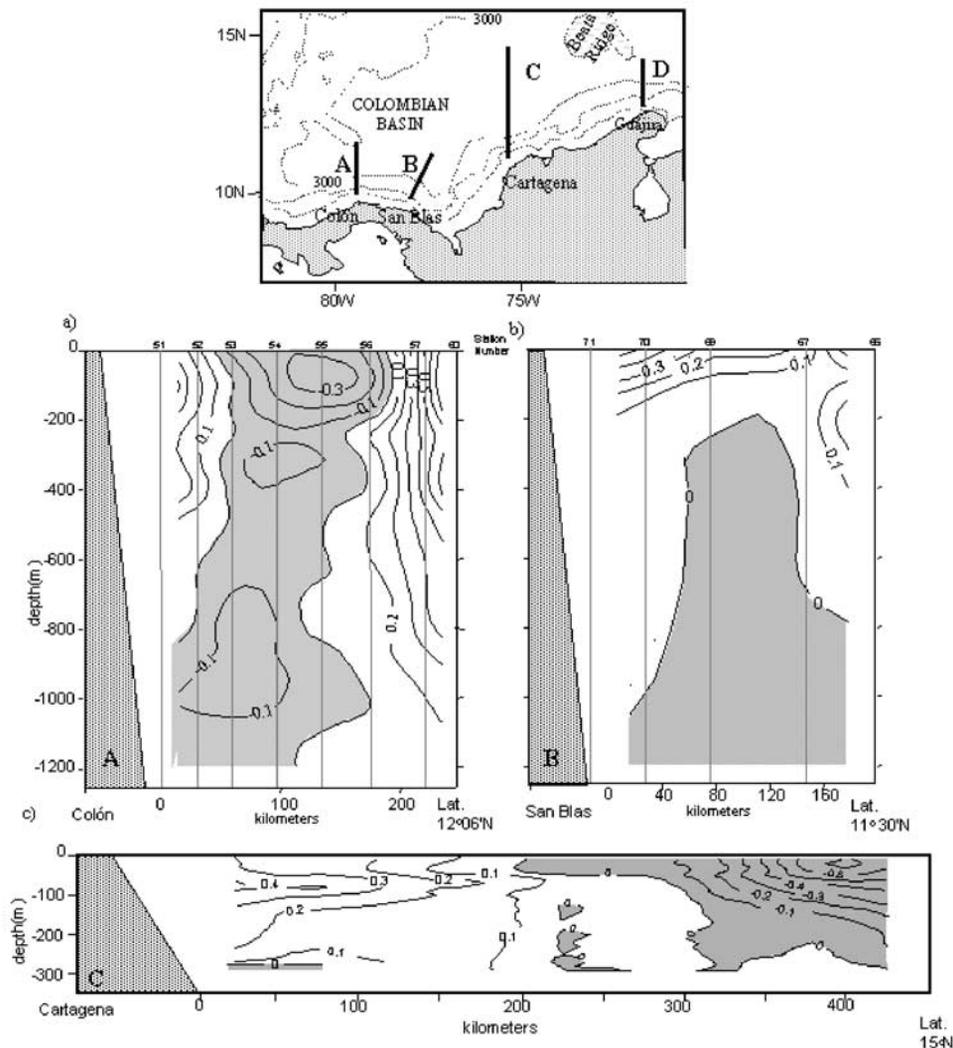


Figure 3. Coastal currents in the southwestern Caribbean Sea. Sections A and B made in July 1997 by R/V *Providencia* show geostrophic speeds referenced to 1200 dbar. Section C show ADCP data taken by R/V *Columbus Iselin* in 1992 along 75°W , redrawn from *Rooth* [1992]. Shaded areas represent westward flow. The coastal eastward flow is evident in every section with maximum speeds at the surface off Panama and in a core around 100 m depth off Colombia. Section D is described in Figure 4.

data were downloaded every 10 m from 30 to 300 m depth as absolute currents from the NODC database.

[10] Volume transport (in sverdrups) was calculated by the discrete integration of the geostrophic velocities in 10-m bins between pairs of stations until the maximum common depth was reached. In this way, there is no estimated transport at levels below the chosen reference level or deepest common depth. In most sections the CTD casts did not reach the bottom and some of them just represent 30% of the water column (i.e., the first 1200 m in 3500 m depth). However, since the assumed reference level corresponds to the near zero velocity observed in available ADCP data, these calculations provide a reasonable estimate of the transport of the upper layers, within the uncertainties of the method used. Generally, no stations were made within 24 km of the coast so no estimates are available nearshore where significant transport might occur. Despite these limitations, the geostrophic method does

provide valuable information about the subsurface velocities of ocean currents, wherever direct estimates with an ADCP are unavailable.

3. Results

[11] Geostrophic computations and current measurements across selected sections provided the zonal component of the coastal currents along the South American Caribbean coast. Results demonstrate the continuity and evolution of the flow, from Central American waters in the west to the Atlantic Ocean in the east.

3.1. Coastal Currents in the SWCS

[12] Section A was sampled on 3 July 1997 along 79°W from the coast of Panama to 250 km offshore near 12°N (Figure 3a). The geostrophic flow from the surface to 800 m was eastward within 100 km of the Panamanian coast, with

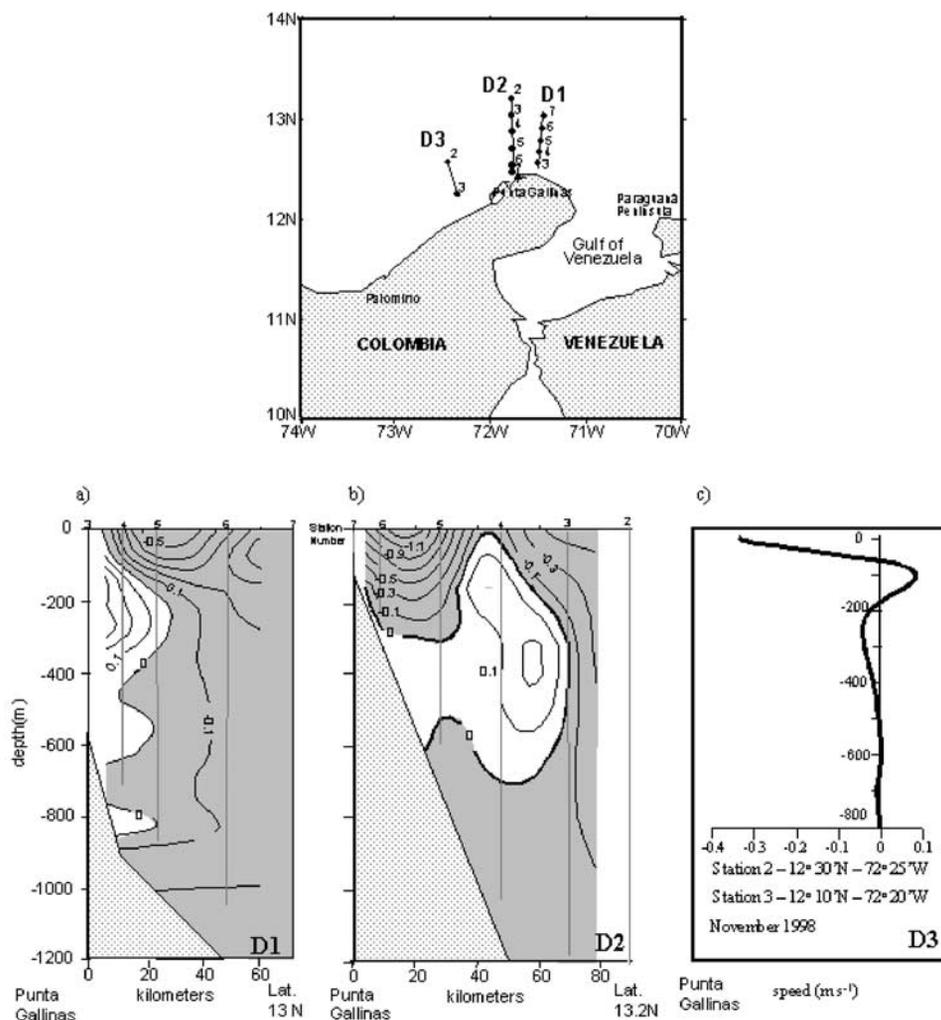


Figure 4. Coastal currents in the Guajira region. (a) Section D1 made in April 1994. (b) Section D2 in February 1998. (c) Profile D3 is the geostrophic velocity between two stations made in November 1998 by R/V *Malpelo*. Shaded areas show westward flow. Every section indicated the presence of an eastward underflow centered around 200 m beneath a westward surface jet associated with the intense upwelling of the area.

maximum speed of nearly 0.4 m s^{-1} . In the center of the section the flow was westward in a 100-km-wide stream with a core at around 80 m. To the north, an eastward flow of 0.7 m s^{-1} extended through the water column. The nearshore eastward flow can be identified as the PCC, the inshore limb of the PCG. Opposing flows in the northern part of the section probably reflect mesoscale anticyclonic eddy activity in the region [Andrade and Barton, 2000].

[13] Section B was sampled on 5 July 1997 between the center of the Gulf of Darien and the San Blas Archipelago. The geostrophic flow (Figure 3b) included the shallow (<200 m) eastward PCC with a maximum speed of 0.5 m s^{-1} off the Panama coast. At greater depths offshore, the flow had westward velocities up to 0.10 m s^{-1} , that reached their shallowest level (250 m) between Stations 67 and 69.

[14] Section C was sampled in the upper 300 m off Cartagena with an ADCP by R/V *Columbus Iselin* on 8 April 1992 (Figure 3c). The broad, westward Caribbean Current, with its near-surface core of 0.6 m s^{-1} at 400 km

off Cartagena, was the dominant feature. In the Colombian Basin this flow forms the northern limb of the PCG. The PCC extended over 200 km from the coast, with a core of maximum speed of around 0.4 m s^{-1} at about 90 m. This direct observation of the PCC is consistent with the results of the previous sections, despite the difference in month and year, in revealing surface layer eastward flow nearshore and generally westward flow offshore. The greater depth and breadth of the eastward flow and the stronger ADCP velocities possibly represent seasonal changes (ADCP data were taken in April at the end of the windy season while the CTD stations were occupied in July at the beginning of the rainy season) and transients.

3.2. Coastal Currents in the Guajira Region

[15] The Guajira Peninsula, the northernmost extension of South America, lies at the midpoint of the South American Caribbean. Its deserts coastline extends over 500 km parallel to the year-round North Trade Winds. It therefore

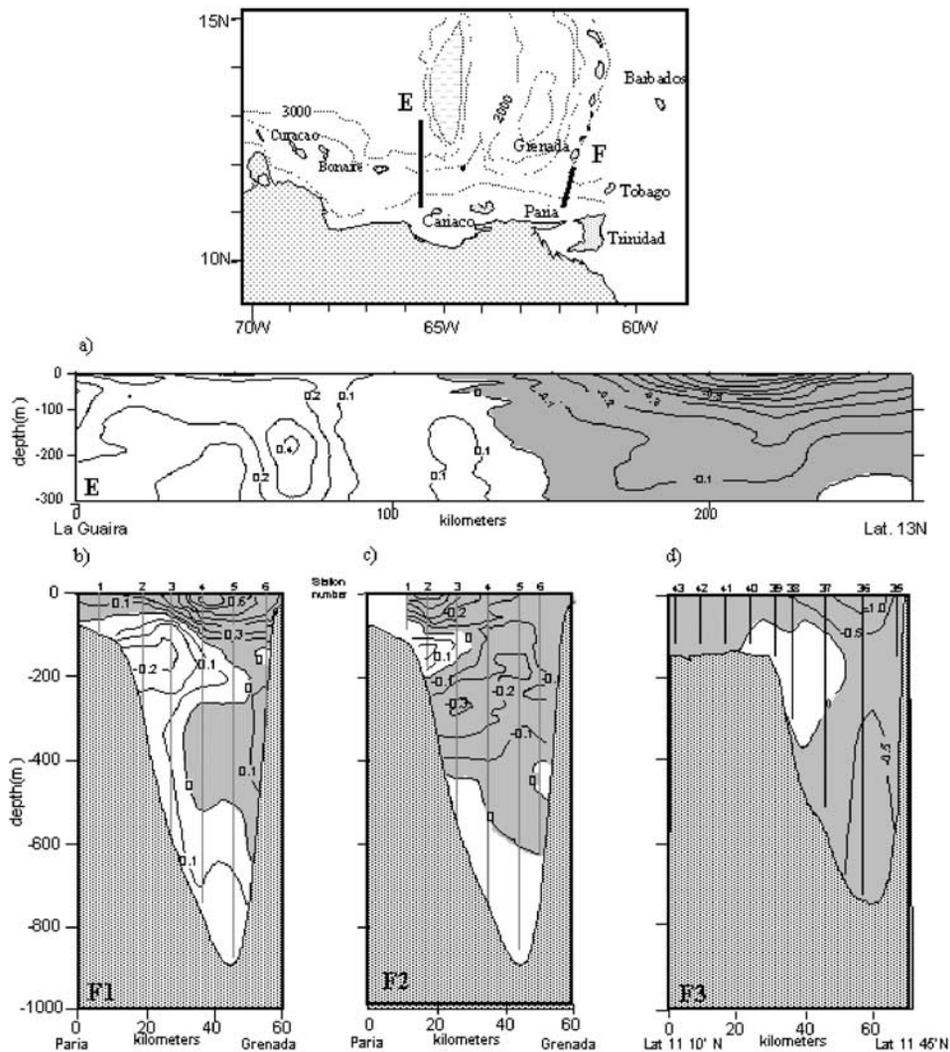


Figure 5. Coastal currents off Venezuela. Shaded areas are westward flows. The coastal eastward flow was present in every section studied. The core of maximum speed was centered at about 200 m depth. (a) Section E is an ADCP section to about 300m made by R/V *Knorr* in August 1997 [Hernández-Guerra and Joyce [2000]]. Undercurrent-related eastward transport was about 7.9 Sv. (b, c, d) Along-channel component of velocity in the Grenada Channel taken from *Wilson and Johns* [1997] for two ADCP sections and one CTD section. Different characteristics of the undercurrent exiting the Caribbean Sea are examined. Undercurrent-related outflow transport of was about 0.9 Sv in May 1992 (Figure 5b) and about 0.5 Sv in April 1994 (Figure 5c); it was about 0.5 Sv during 19–20 March 1970 (Figure 5d), taken from *Wilson and Johns* [1997], redrawn from *Stalcup and Metcalf* [1972].

experiences strong coastal upwelling [Gordon, 1967; Corredor, 1979], albeit with significant seasonal variability [Andrade, 2000]. The Guajira faces the Aruba Passage, which joins the Colombia and Venezuela Basins.

[16] North off Punta Gallinas (Figure 4) a strong westward surface jet and an opposing sub-thermocline eastward undercurrent typified the upwelling system. Along section D1 (71°30'W), the surface westward coastal jet was relatively weak (maximum speed $>0.5 \text{ m s}^{-1}$) and the eastward undercurrent was narrower and slower extending only 30 km offshore with maximum speed of 0.3 m s^{-1} at around 200 m (Figure 4a).

[17] Section D2 was sampled in February 1998 during the peak of the windy season along 71°40'W; the geostrophic

flows had a stronger westward surface coastal jet ($>1.3 \text{ m s}^{-1}$) centered on 12°50'N and a weaker but more extensive eastward flow of $\sim 0.2 \text{ m s}^{-1}$, 50 km off the coast at around 300 m (Figure 4b).

[18] Only two stations from Section D3 on the continental shelf off the Guajira Peninsula in November 1998 were deep enough to examine the geostrophic current profile (Figure 4c), which suggests a persistence of upwelling during this season of usually weaker Trade winds. The surface westward jet reached a speed of 0.3 m s^{-1} and the eastward undercurrent was located at about 100 m with a speed of 0.1 m s^{-1} . Although the sampling of this presumably variable upwelling area was limited, during and at the end of the windy season the upwelling jet was about three

Table 1. Geostrophic Transport of the Caribbean Coastal Countercurrent Calculated Across the CTD Sections

Section	Name	(in Sv)	Date
A	Colon	5.8	July 1997
B	San Blas	5.7	July 1997
D1	Punta Gallinas 1	0.9	April 1994
D2	Punta Gallinas 2	1.9	February 1998
F3	Grenada Channel	0.5	March 1970

times as strong as in the rainy season and the undercurrent was up to twice as strong and always present.

3.3. Coastal Currents Off the Venezuelan Coast

[19] Section E was sampled as part of a long transect surveyed in August–September 1997 with an ADCP and CTD from La Guaira along 66°W during WOCE [Hernandez-Guerra and Joyce, 2000]. The flow was eastward near the Venezuelan coast with a core speed of 0.4 m s⁻¹ at 200 m near 11.5°N. The westward Caribbean Current jet had speeds (>1.0 m s⁻¹) at the surface near 13°N (Figure 5a).

[20] Historical hydrographic data of different years taken in the Venezuelan and Grenada Basins were used in previous studies [Gordon, 1967; Roemmich, 1970] to estimate the currents. These eastern sections indicated a coastal flow with a subsurface core and structure similar to the sections shown here. Although the geostrophic speeds were low, they do qualitatively support the existence of the eastward flow.

4. Analysis and Discussion

[21] Poorly known aspects of the general circulation along the South American coast in the Caribbean have been examined. The geostrophic computations and current measurements permitted the analysis of the subsurface structure of known features in the Colombian Basin such as the Panama-Colombia Countercurrent. The continuation of the countercurrent beneath the Guajira and Cariaco upwelling systems has been identified.

[22] The PCC appeared as a surface eastward flow trapped against the coast in all sections off the Panamanian and Colombian coasts. A general caveat is that the stations nearest to the coast of Panama are ~24 km offshore in these sections. This fact has implications for the volume transport calculations of the coastal currents (Table 1), since it is possible that a significant portion of the flow was missed. However, there was eastward flow in every section sampled, including other short ones not included here for brevity. The transport was greatest off the Panamanian coast and weakened along the Colombian coast. There was a major decrease in transport where the PCG separates from the coast west of Cartagena and meets the westward Caribbean Current. This pattern is similar to the Northwest African System where the Canary Current separates from the coast near 20°N. South of there a closed circulation (the Guinea dome) is found with nearshore poleward flow extending up to the surface. The poleward flow continues northward as a subsurface flow at 300 m depth with much reduced transport [Barton, 1998]. Similarly, where the California Current separates from the coast south of the Baja California peninsula, the northward Costa Rica current extension

continues as a subsurface flow [Badan-Dangon *et al.*, 1989].

[23] The decreasing transport in the eastward coastal flow off Panama indicates that water is lost from the coastal regime northward. Most of the water is transported farther offshore toward the north-northwest. The overall eastward flow in July 1997 decreased from 5.8 Sv across 79°W and 5.7 Sv leaving the Gulf of Darién across 75°W to just ~1 Sv along the Colombian coast near the Guajira at 72°W.

[24] In the Guajira region, the eastward undercurrent was present in the different seasons. It transported ~2 Sv during the windy season and about half of that (~1 Sv) during the transition season. The coastal eastward flow was evident off the Venezuelan coast, reaching the surface and transporting 7.9 Sv. Stepanov *et al.* [1978] observed a small surface cyclonic circulation, which they named the Venezuelan Gyre off the central coast, which is probably contiguous with the general countercurrent. The persistent appearance of an eastward flow in this nonsynoptic data set suggests that the flow may be a permanent feature of the circulation in the region joining the Panama-Colombia Countercurrent and the Venezuela countercurrent beneath the westward surface jets produced by the Guajira upwelling. These results suggest there is a flow transporting between 1 and 8 Sv with maximum speeds in a subsurface core at 200 m depth beneath the upwelling systems but throughout the upper few hundred meters elsewhere.

[25] The few available ADCP sections broadly support the indirect estimates of flow. An eastward nearshore undercurrent or countercurrent was observed in every section. The directly observed velocities and therefore transports (Table 2) off Cartagena and La Guaira were much larger than geostrophic estimates (Table 1). These differences may reflect real variability in the magnitude of the flow or possibly transient effects. Systematic sampling is required to define the counterflow and its variability in detail.

[26] Direct measurements [Wilson and Johns, 1997] define a localized eastward flow at Grenada Passage (11°25'N) centered around 200 m depth (Figures 5a and 5c), very similar to the undercurrent found off the Guajira Peninsula and off La Guaira. It also appeared in the observations made in March 1970 (Figure 5d) reported by Stalcup and Metcalf [1972]. In both cases the transport (Table 2) is compatible with the geostrophic estimates off Guajira of 1 Sv or less. This flow conveys water from the Caribbean into the tropical Atlantic Ocean, which strongly suggests that the Caribbean Countercurrent/Undercurrent continues along the South American coast. An alternative scenario for the countercurrent is that it separates from the continent to flow northward inside of the Antilles Arc and returns westward along the northern boundary of the Caribbean. Flow along the northern limit of the Caribbean is

Table 2. Measured Transport of the Caribbean Coastal Countercurrent Calculated Across the ADCP Sections

Section	Name	(in Sv)	Date
C	Cartagena	11.2	March 1992
E	La Guaira	7.9	August 1997
F1	Grenada Channel	0.9	May 1992
F2	Grenada Channel	0.5	April 1994

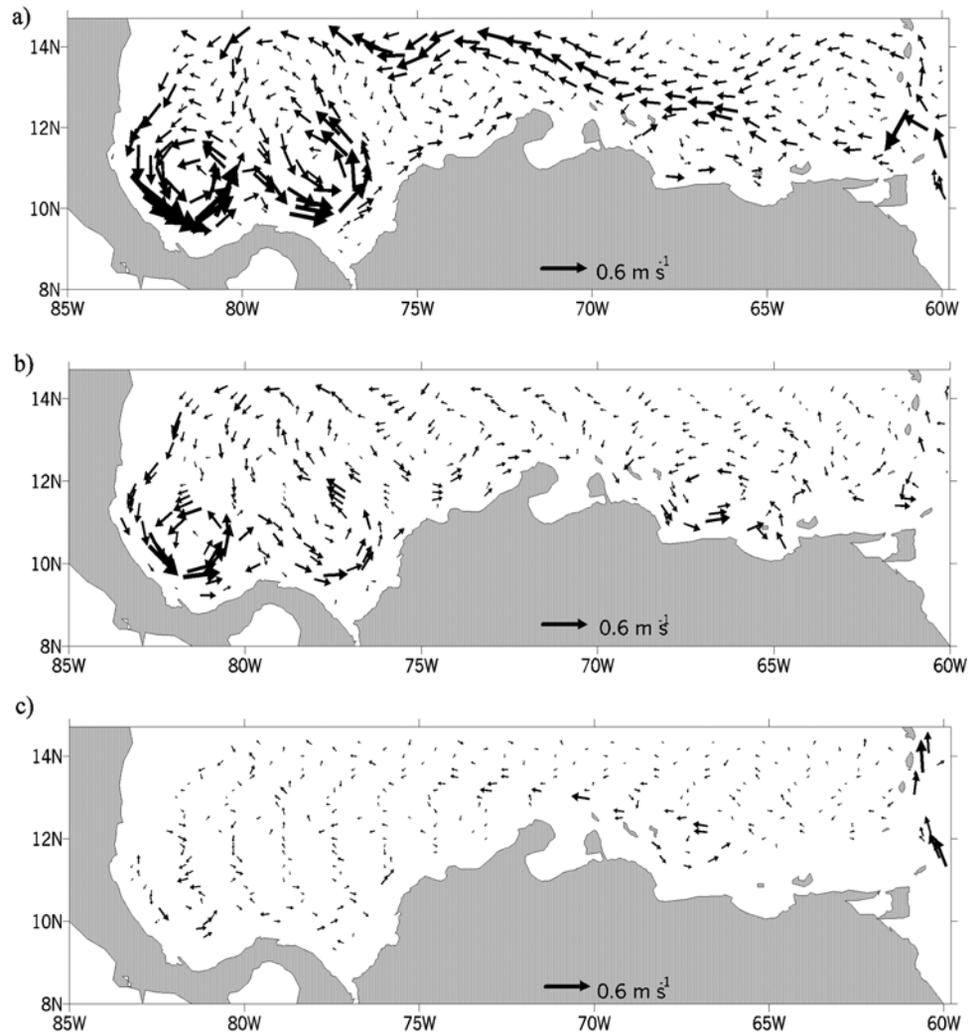


Figure 6. Snapshot of the South American coast subdomain of IAS-POM at (a) 50 m, (b) 200 m, and (c) 800 m. The flow at 50 m depicts several cyclonic eddies off the South American coast south of the Caribbean Current axis. The flow at 200 m shows the coastal eastward undercurrent as a “thin” stream that can be followed off the coast, enhanced by the shallow cyclonic eddies associated with the upwelling systems of Guajira and Cariaco. The model is consistent with undercurrent outflow in Grenada Passage. The flow at 800 m shows that most cyclones are limited to shallower depths except those at Gulf of Mosquitos and Cariaco.

clearly westward in the ADCP section of *Hernández-Guerra and Joyce* [2000], but data along the Caribbean continental shelf of the Lesser and Greater Antilles are too limited to reach a definite conclusion.

4.1. Modeling the Undercurrent

[27] The numerical model used to study the circulation in southern Caribbean Sea is the Princeton Ocean Model (POM) [Blumberg and Mellor, 1987] implemented for the Intra-Americas Sea, with 20-km horizontal resolution and 21 vertical (sigma) levels for a domain between 5°N and 30°N and 55°W and the IAS coast. It uses an edited version of the DBDB5 (ETOPO5) topography and locates the model coastline on the 20-m isobath. It has been forced with geostrophically balanced flow and mass fields at open lateral boundaries using the *Ocean Climate Laboratory* [1994] climatology. The model then develops the velocity

field, and accommodates the mass and velocity fields to the bottom topography and wind field. Wind-forcing is the *Hellerman and Rosenstein* [1983] climatological monthly mean wind stress and steady climatological geostrophic inflow on the eastern boundary which is constrained to provide 32 Sv of throughflow. All the major circulation elements are generated, plus plausible mesoscale variability. Here snapshots are presented of a slowly varying regime that has mesoscale variability as well as seasonal variations. They are considered representative synoptic fields of a well spun-up model.

[28] In the synoptic maps (“snapshots”) of the currents at 50, 200, and 800 m in the southern Caribbean Sea, a series of cyclonic circulation cells dominate the flow field along the southern boundary. In the 50-m map, the Caribbean Current meanders through the entire basin accompanied by a series of cyclones. Those in the Gulf of Mosquitos and

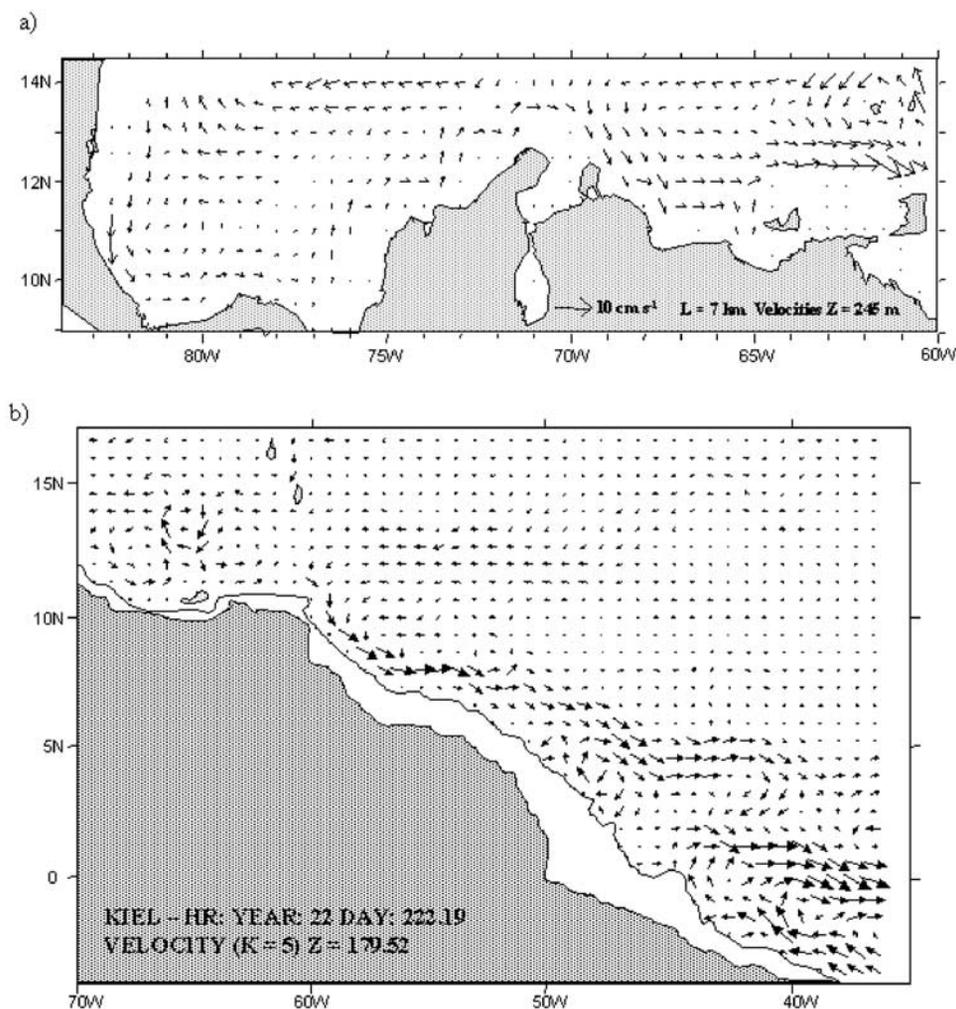


Figure 7. (a) Velocity field of the Caribbean Sea at 245 m from the MOM output redrawn from *Sou et al.* [1996] showing the coastal Caribbean eastward flow. (b) Model velocity field at 179 m in August, from IFM model of *Wilson et al.* [1994] showing the coastal eastward flow exiting the Caribbean. These models outputs and the results shown here suggest the Caribbean Coastal Undercurrent connects with the North Equatorial Undercurrent outside the Lesser Antilles, closing the Tropical Cell of the Sverdrup circulation of the Atlantic.

Gulf of Darien (the PCG) are especially intense (Figure 6a). There is also one cyclone associated with the Guajira upwelling and the one in the Cariaco Basin (the Venezuela Gyre).

[29] The agreement between simulated currents at 200 m in the Colombian Basin in IAS-POM and the observations is encouraging. The model results suggest that there is intense mesoscale variability in the SWCS associated with the PCC subsurface core around that depth (Figure 6b). The model flows clearly indicate the eastward coastal currents observed in the Venezuelan and Grenada Basins. The undercurrent in the model output can be traced as a “thin belt” just off the coast that is enhanced/diminished by the presence/absence of cyclonic cells along the coast. It is a semicontinuous flow that weakens as it flows eastward from Panama to Colombia and remains roughly constant along the Venezuelan coast. The model simulated the undercurrent along the Guajira Peninsula beneath the upwelling system as part of another smaller cyclone that connects with the

coastal eastward flow off La Guaira and Cariaco associated with the Venezuelan Gyre. The observed outflow of the undercurrent in Grenada Channel was also simulated.

[30] Simulated currents at the 800-m level demonstrated that most cyclones are shallower, except the one in the Gulf of Mosquitos (Figure 6c). The Caribbean Current core is still strong along the Leeward Antilles and off Guajira. The northward Antilles Current is a notable flow off the Windward Antilles outside the Caribbean, and an opposite flow (southward) is apparent inside the Grenada Basin. Coastal eastward flow is apparent in the Colombian and Venezuelan Basins, but the two flows are unconnected at this level.

[31] The model results generally suggest meandering of the flow along the coast, which may explain variability in transport and position of the maximum speed encountered in closely separated sections. Furthermore, the presence of cyclones interacting with the Undercurrent may be responsible for the variability found in the geostrophic calculations and direct current measurements.

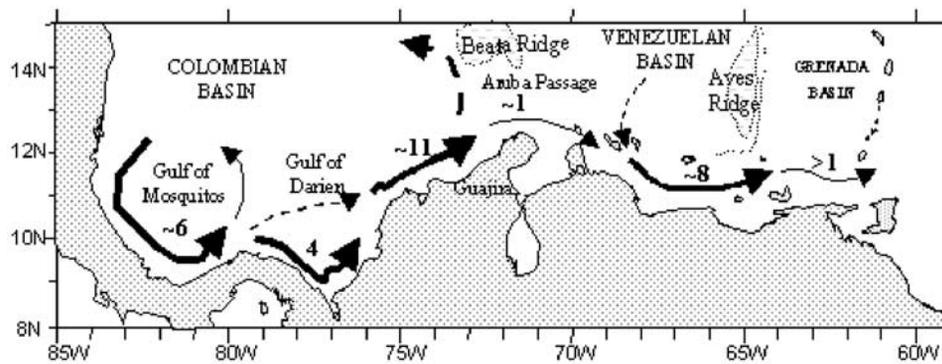


Figure 8. Schematic representation of the southern Caribbean Coastal Undercurrent as it was found in the different sections studied along the coast. The width of the arrows represent the current intensity at 200 m depth together with the averaged Undercurrent geostrophic transport (in sverdrups). Water leaves the coastal current between the Gulf of Mosquitos and the Gulf of Darien, and again off Guajira. The Undercurrent transport is augmented off the coast of Venezuela but less than 1 Sv exits the Caribbean Sea.

[32] Other models also indicate the existence of the undercurrent. In an exercise to test the parameterization of topographic stress in the Caribbean Sea with the Modular Ocean Model (MOM), *Sou et al.* [1996] described the undercurrent off the South American coast (Figure 7a). Also, the flow field calculated by *Schott and Boning* [1991] in the Institute für Meereskunde model-Kiel Community Modeling Effort model data at 179 m (Figure 7b) indicated that the undercurrent is “feeding” the North Equatorial Undercurrent outside the Lesser Antilles [*Wilson et al.*, 1994] from the eastward flow at Grenada Passage, raising appealing evidence for the closing of the Tropical Cell of the Sverdrup circulation of the Atlantic.

5. Conclusions

[33] Collation of 10 hydrographic sections made in different months and years along the Central and South American coast of the Caribbean strongly suggests the existence of an eastward flow from Panama to the Antilles, counter to the Caribbean Current. Three sections in the Colombian Basin, three in the Guajira region, one in the Venezuelan Basin, and three in the Grenada Basin show the coastal eastward flow with maximum velocities in a subsurface core (the Caribbean Coastal Undercurrent). A schematic representation of these results is provided in Figure 8. This eastward flow corresponded with the expected direction for the cyclonic Sverdrup cell in the Tropical North Atlantic. However, there is not enough evidence to conclude this is a fully continuous flow.

[34] The Panama-Colombia Countercurrent was evident to the west of 79°W. It was strongest (~6 Sv) off the Panamanian coast but most of its transport was recirculated in the Southwest Caribbean Gyre instead of continuing along the Colombian coast. However, a portion (~1 Sv) of the flow continued eastward along the Colombian and Venezuelan coasts. Variations in transport and maximum current speed between sections reflect significant seasonality and mesoscale variability.

[35] East of the SWCS, the flow is an undercurrent that has maximum speeds at around 100 m in the Colombian Basin, and subsequently deepens and shoals as it travels

eastward. The core of maximum speeds (typically 0.1 m s^{-1}) is at 200 m beneath the Guajira upwelling system, and again at 200 m beneath the Cariaco upwelling system.

[36] Some of the numerical simulation results at subsurface levels depict the core of the undercurrent as a weak (~1 Sv) coastal stream that passes the Guajira peninsula to the east, flowing between the Leeward Antilles and the Venezuelan coast. The undercurrent flow is enhanced by the continuous formation of cyclones off the coast of South America. This fact may explain the great variability of the eastward transport along the coast.

[37] The Sverdrup circulation in the North Atlantic tropical cell implies a mean southeastward transport of about 5 Sv, along the Central and South American coasts. This result from Sverdrup circulation theory supports the existence of the PCC and its eastward subsurface continuation presented here. A detailed examination of the transport showed significant variation (over the range 0.5 to 11.2 Sv) around the expected 5 Sv. However, Sverdrup theory gives a linear, large scale, integral effect and these results represent “snapshots” of instantaneous, transient flow rather than a steady flow. The countercurrent/undercurrent dynamics probably depend on the alongshore pressure gradient set up against the Central American boundary and the time-varying wind, among other mechanisms.

[38] Mesoscale activity plays an important role in the variability of the Panama-Colombia Counter current and the other regional features. The turbulent nature of the boundary current, exemplified by eddies intersecting the boundary current and coastal upwelling filaments, may render the flow discontinuous, especially in the Lagrangian sense. The ecological implications of connectivity between the Southwestern Caribbean, the Guajira and Cariaco upwelling systems via the Undercurrent over a period of a few months, may be of great interest for future research.

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