The Guajira Upwelling System

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Abstract

The coastal upwelled waters of the Guajira coast, the most northerly peninsula of South America, were studied on the basis of historical and remotely sensed data, and three oceanographic cruises. The Guajira Peninsula is the locus of particularly strong upwelling because it protrudes into the Caribbean Low Level Wind Jet and its west coast parallels the direction of the strongest winds. The year-round upwelling varies with the wind forcing: strongest in December-March and July, and weakest in the October-November rainy season. The east-west temperature, salinity and density front that delimits the upwelling lies over the shelf edge in the east of the peninsula but separates from the south-westward trending topography to the west. A coastal westward surface jet geostrophically adjusted to the upwelling flows along the front, and an eastward sub-surface counterflow is trapped against the Guajira continental slope. The undercurrent shoals toward the western limit of the upwelling, Santa Marta, beyond which point it extends to the surface. Some of the westward jet re-circulates inshore with the counterflow but part continues directly west to form an upwelling filament. Much of the mesoscale variation is associated with upwelling filaments, which expel cooler, chlorophyll-rich coastal upwelling waters westward and northward into the Caribbean Sea. Freshwater plumes from the Magdalena and Orinoco rivers influence the area strongly, and outflow from Lake Maracaibo interacts directly with upwelled waters off Guajira. Another important factor is the Aeolian input of dust from the Guajira desert by episodes of offshore winds.
1. Introduction

The Guajira Region, the northernmost tip of South America, comprises the area between the Peninsulas of Guajira and Paraguaná, which protrude into the Central Caribbean beyond 12ºN. This flat and desertic region, only a few hundred metres in elevation, extends 600km from Puerto Cumarebo, at 69ºW in Venezuela, to the Sierra Nevada de Santa Marta, at 74ºW in Colombia (Fig. 1a). The two peninsulas enclose the Gulf of Venezuela, at the mouth of Lake Maracaibo, the location of major oil exploitation.

The persistent and intense Caribbean Low Level Jet of the North Trade Winds blows almost parallel to the Guajira coast to produce a coastal upwelling recognised in a number of studies (e.g. Wust, 1963; Gordon 1967; Fajardo, 1979; Andrade, 2000). Recently, satellite observations of ocean colour (Müller-Karger et al., 1989; Andrade, 1995) have revealed the highly variable interaction between the continental shelf upwelling regime and the offshore Caribbean Basin regime. The boundary between the cool, nutrient-rich upwelled waters and the warmer, nutrient-poor offshore waters is irregular and often contorted into long, narrow, offshore-flowing streamers or filaments of upwelled water that may reach far offshore (Figure 2). Similar structures have been documented in other parts of the world (e.g. Flament et al., 1985; Brink and Cowles, 1991, Barton et al., 1998), where they have been found to be responsible for significant export from the shelf to open ocean. Filament waters are typically rich in nutrients and high in chlorophyll because of their origin in the nearshore upwelling (Navarro-Perez and Barton, 1998).

The Guajira upwelling and its associated structures have not previously been studied in detail, and in situ observations in this region are scarce. In this article, a series of oceanic historical data, recent in situ measurements, satellite images, and satellite altimetry of the Guajira Region are discussed in terms of the annual cycle and the sources of variability. The Guajira upwelling region is important because it supports a fishery through enhanced primary production. The intense shelf-ocean exchange associated with the upwelling and filaments may play major role in horizontal mixing of the upper ocean and in distributions of fish eggs and larvae.

2. Data

Field data were obtained during three cruises: 1) R/V Malpelo 14-22 April 1994 (Fig. 1a) 2) R/V Providencia 17-19 February 1998 (Fig. 1b) and 3) R/V Malpelo 20-25 August 1998 (Fig. 1c). Cruise sampling patterns varied because of logistic constraints. Spacing between stations was about 50km in the oceanic region and 5km at the tip of the Guajira Peninsula. Data were acquired with a Sea Bird SB-19 Conductivity-Temperature-Depth (CTD) probe to 1200m or the seabed where shallower. The profilers were calibrated by the manufacturer before 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 determined with a Beckman inductive salinometer.

Geostrophic calculations for each oceanic section used a reference depth of 1200 m, the maximum depth in most stations, which has been used previously in the Caribbean Sea.
(Gordon, 1967; Roemmich, 1981). We conclude it is an adequate level from examination of Lowered ADCP data of Joyce et al., (2001), which show minimum speeds around that level. Where the bottom depth was shallower than the reference level, the method of Reid and Mantyla (1976) was used.

Sea surface temperature (SST) images were obtained from High Resolution Picture Transmission (HRPT) data from the Advanced Very High Resolution Radiometer (AVHRR) sensor of the US National Oceanic and Atmospheric Administration (NOAA) satellites captured at the Centre of Investigations in Oceanography and Hydrography (CIOH) in Cartagena (10° 25' N, 73° 24' W). Distinct multi-channel algorithms were used for night time and day time images (McClain, 1982). SST is calculated with an accuracy of about 0.5°C. The images were plotted on a Mercator Projection with a 1-km pixel resolution.

Surface chlorophyll data were from two sources. Coastal Zone Color Scanner (CZCS) images compiled at the NOAA - NESDIS- Oceanic Research and Application Division were retrieved for August-September 1979. Sea-viewing Wide Field of View Sensor (SEAWIFS) images were downloaded from the mission website at www.seawifs.gsfc.nasa.gov for periods in 1998.

Sea level anomaly maps, calculated from satellite altimetry at the Colorado Centre for Astrophysics Research, were downloaded from the web site www-ccar.colorado.edu. These maps are composites of near-real-time passes of TOPEX-POSEIDON and ERS-2 over the Caribbean updated every three days. The geostrophic velocity was calculated from the sea-level anomaly assuming a “level of no-motion’ at 1000m depth in the automatic procedure, since that depth was the closest to the 1200dbar chosen in the geostrophic calculations in this study.

3. Seasonal Variation

In the Caribbean, the strong alongshore component of the North Trade Winds drives upwelling at the southern boundary, along 1200km of the Colombian and Venezuelan coast (Fig. 2). Two main zones particularly favourable for upwelling because of the coastal orientation are around Margarita Island (11ºN, 64º 15'W) in the Eastern Caribbean (e.g. Febres-Ortega, 1978; Muller-Karger et al., 1989) and in the Guajira region in the Central Caribbean.

Large-scale upwelling is apparent in the long term monthly mean SST fields extracted from the NOAA World Ocean Data (1994) for the months of the three cruises (Fig. 3). The zone of lower mean coastal temperatures extends westward to Santa Marta (11ºN, 74ºW). The general form of the sea surface temperature fields shows that the typical cooler region of upwelling near the Guajira coast persists year round. The western limit of the upwelling in the windy season is clearly Santa Marta, at the boundary with the Panama-Colombia Gyre (Andrade et al., 2003). West of Santa Marta near-shore waters are consistently warmer than offshore.

Andrade (1993) has shown that the monthly mean wind speed over the waters of the Guajira region remains near 10 m s⁻¹ throughout the year. However, there is a typical annual variability consisting of a windy, dry season from December to February, a mid-summer dry period in July-August - again of slightly stronger winds, and the season of strongest rains and weakest winds from September to November. Ekman transport has a major component normal to the coast, with maximum values around 1 Sv per 1000km alongshore in the windy season (Andrade, 2000). The annual march of the wind vector for the Central Caribbean along 72W is shown in Fig. 4a. In this area, the direction of the mean monthly winds has a strong westward component year-round. When the winds are strong from December to March, the direction is more south-westward, parallel to the Guajira coast. The Low Level Jet (LLJ) is
evident throughout the year as a maximum of wind speed at 15ºN.

The meridional temperature gradient between the coast and 15ºN (Fig. 4b) strengthens in December-March and in July because of the increased upwelling at the Guajira coast during the windy season and mid-summer dry spell. The least intense upwelling, indicated by a period of minimal temperature gradient, occurs in the rainy season when the winds are weakest and most variable in direction.

The mean seasonal variation of the vertical temperature structure of the upwelling region north of the Guajira Peninsula is shown in Fig. 4c. The data are monthly averaged values for the area (12-13ºN, 72-73ºW) calculated from NOAA World Ocean Data (1994). At this latitude, mean seasonal variation of SST is about 2.5ºC. Wind stirring during the windy season is sufficient to weaken the seasonal stratification from December to May. The maximum penetration of the surface mixed layer is no more than ~50m. The seasonal thermocline begins to transform in April and reaches its strongest when wind forcing is minimum during the October rainy season.

The wind stress curl calculated at a 2.5º interval from the above wind data provided an estimate of mean vertical velocity at the base of the Ekman layer of $4.4 \times 10^{-5}$ m s$^{-1}$. This result indicates an upward velocity or open ocean upwelling almost year-round between the coast and the axis of the LLJ, as expected. Maximum values of estimated monthly mean upwelling velocity were around 114 m month$^{-1}$, but the divergence is under-estimated at the coast because of the 2.5º spacing of the observational grid.

4. Mesoscale Variability

Recent satellite and field observations indicate strong year-round mesoscale variability in temperature and sea-level anomaly distributions in the Guajira Region that is superimposed on the background seasonal and regional variations (Andrade and Barton, 2000). Here “mesoscale” refers to the range of phenomena whose dominant spatial scale lies between approximately one and ten times the baroclinic Rossby radius and temporal scale of one to ten inertial periods. At 12ºN, the inertial period is ~14 days in the Guajira Region, and the baroclinic Rossby radius ($R = NH/\pi f$, where $N$ is the Brunt-Vaisala buoyancy frequency, $H$ the mean depth, $f$ the Coriolis force) is ~30km. Thus, the term “mesoscale” encompasses tens to several hundred kilometres and periods of about two weeks to several months.

It is shown below from a combination of remote sensing and in situ data that mesoscale variability in the Guajira region is characterised largely by coastal upwelling phenomena, including a coastal upwelling jet and countercurrent. As in other regions, convoluted upwelling filaments of relatively high chlorophyll and low temperature extend the coastal influence seawards. Unlike most of the major upwelling areas, there are clear effects of outflow from large river systems separated along the coast.

4.1 Upwelling Filaments

AVHRR and colour satellite images reveal that the upwelled waters of the Guajira region form narrow, cool, chlorophyll-rich filaments extending some hundreds of kilometres offshore. Two of these features were tracked during the windy season of 1998. Four images reveal the development of one filament (A in Fig. 5) over 17 days. On 8 January 1998 the filament had its origin on the Guajira continental shelf near 12.5ºN just north of Cabo de la Vela (Fig. 5a). It can be distinguished as the narrow tongue of cooler water of ~25 ºC
extending over 250 km offshore to the northwest. The later images show that the Paranaguá upwelling fed indirectly into this filament too. The images of 10 and 21 January indicate the filament was advected westward by the Caribbean Current, while remaining linked to the upwelling centre (Fig. 5b, c). The net current calculated from the displacement of the windward front was \(-0.6 \text{ m s}^{-1}\) at 200 km off the coast and \(-0.4 \text{ m s}^{-1}\) at the base of the filament. The filament was more tenuous and narrower in the later images and appeared shorter by the end of the sequence on 25 January (Fig. 5d). The cyclonic, rounded feature labelled C, of slightly lower sea-surface temperature, was tracked in later satellite altimetry maps, as detailed below.

Another filament formed upstream of the Peninsula of Paraguaná during March 1998, growing over 350 km in 25 days (B in Fig. 6a, d). The tip of the filament, though partially obscured by cloud, was first detected offshore of Cape San Roman around 5 March and subsequently tracked north-westward until March 30, when it reached the central part of the Caribbean, close to the 5 January position of the filament described earlier. The speed associated with the growth of this filament during its later development was about 0.15 m s\(^{-1}\).

Filaments arising in the western part of the Guajira upwelling elongate the upwelling center westward to create a large area (~850 km\(^2\)) of cool water. The resultant large filament may reach the waters off Central America, 1200 km to the west, as happened in July 1997 (Fig. 7a). Moreover, filaments produced in the eastern part of the Guajira system may extend 400 km northward to cross the Central Caribbean as on 1 August 1998 (Fig. 7b and c). The northward extending filaments were \(-70 \text{ km wide}, and reached as far as 14 to 16\(^\circ\)N. The filament that extended westward in Fig. 7a was more than 150 km wide, and reached over 600 km from its origin. The coastal boundaries of the northern and western Caribbean are just beyond the limits of these images; hence, the variability of these mesoscale phenomena affects the entire domain of the Central and Western Caribbean.

The CZCS images show highest chlorophyll values near the Guajira coast inside the temperature front that delineates the offshore edge of the upwelling centre. A tongue of higher chlorophyll extending north-westward indicated the path of a filament in August 1979 (Fig. 7c). Chlorophyll decreased irregularly along the filament. CZCS chlorophyll images also reflect the permanent abundance of phytoplankton in the Gulf of Venezuela. The occasional great extension of the filament temperature signal occurs also in the chlorophyll patterns. For example, Fig. 7d indicates that chlorophyll generated in the Guajira upwelling system spread to the western Caribbean in filaments extending as far as 16\(^\circ\)N, probably reaching the northern boundary of the Caribbean.

The January 1998 filament of Figure 5 was tracked in altimetry analysis until March by contouring the sea-surface anomalies of the TOPEX-POSEIDON and ERS-2 satellite tracks over the region. The sequence of sea surface height anomaly maps of Figure 8 indicates formation of the cyclonic eddy C by 13 January. For clarity, only contours related to the filament and eddy structure are retained in the plots. The eddy was splitting from the filament by mid-January and then migrated slowly northwestward at about 0.04 m s\(^{-1}\) to reach Jamaica by the end of March, 75 days later.

**4.2 River runoff**

CZCS data suggest that the origin of the large pigment patch to the west of the Guajira is the Magdalena River (Fig. 7c). Since water of this river flows through a land area of mean ambient temperature \(-35\(^\circ\)C), the outflow can be detected as warm patches in the AVHRR imagery, for example (Muller-Karger et al., 1991). In the oligotrophic waters of the western Caribbean,
nutrients from the Magdalena should be rapidly taken up by plankton, and concentrations will decrease rapidly with distance from the river mouth.

The general westward flow prevents water from the Magdalena intruding into the upwelling system; however, warm and fresh water from Lake Maracaibo is evident in the AVHRR images (e.g. Fig 5c) and may perturb the measurements of productivity in the Guajira area.

Pigments from the Orinoco River delta, 1000 km to the east, may be traced as far as the Central Caribbean (Müller-Karger et al., 1989, Corredor et al., 1996). Entrainment of the Orinoco plume around a large cyclonic eddy was documented by Corredor et al. (2004) with ocean color imagery and in situ observations. Coloured dissolved organic carbon from the Orinoco river contaminates the remotely sensed colour signal attributed to primary productivity in the Caribbean (Hochman et al., 1994). However, pigment concentration in the plume is sufficiently low to be distinct from the Guajira Upwelling and pigments are good tracers of the spatial extent of the upwelling and filament structures. Nevertheless, caution should be used when discussing upwelling productivity from CZCS or SEAWIFS data in the region.

4.3 In situ observations

The three cruises were made in different tropical seasons. The cruise of April 1994 took place during the transition after the windy season when maximum upwelling begins to weaken; the cruise of February 1998 was at the peak of the windy season and strong upwelling, and the cruise of August 1998 sampled during the rainy season when winds relax and upwelling is weaker (Fig. 4c).

In April 1994, the Guajira Region was sampled on a grid spacing of ~50 km reduced to 5 km in the easternmost sections. Sea surface temperature exhibited a strong front around 12.5ºN (Fig. 9a), within which the Guajira shelf was occupied by water with minimum temperatures of 23ºC. Highest salinities coincided with cool temperatures in the shelf upwelling region (Fig 9b). Based on dynamic topography calculated with respect to 1200m, there was a westward jet along the thermal front, close to the coast at Cabo de la Vela, and a weaker coastal return flow in the westernmost part of the region, forming a cyclonic circulation around the upwelled water “pool” i.e., an upwelling centre (Fig. 9c).

Along section 2 (72ºW) the upwelling was indicated by the 25º isotherm, which broached the surface close to the coast but was 100 m deep about 100km offshore (Fig. 10). The strongest uplift is within one baroclinic Rossby radius of the coast, as expected. Geostrophic currents included a stronger surface westward coastal jet with speeds above 1m s⁻¹ and a subsurface eastward flow of about 0.1m s⁻¹.

The geostrophic surface westward upwelling jet flowing at >0.5 m s⁻¹ and the eastward undercurrent flow (>0.3 m s⁻¹) centred at 200 m depth were also seen in vertical distributions along section 1 at 71.5ºW (Fig. 11a). The upwelling front and jet continued westward across Sections 3 and 4 (Figs. 11b, c) beyond the tip of the Guajira Peninsula along 12.8ºN, separating from the southwestward trending shore. Although both front and jet coincided with the shelf edge in the east, they had separated by up to 170 km from the coast in Section 5 along 74.5ºW, where they remained strong (Fig. 11 d). The strong surface westward motion occurred as a localised jet and was accompanied by an eastward undercurrent. The latter was centred on 200 m depth in the east but appeared at progressively shallower levels in the western region as the surface jet separated from the coast, broaching the surface in Section 5 as the Panama-Colombia Countercurrent.
In February 1998, two oceanographic sections (6 and 7) were made off Cabo de la Vela, this time at the peak of the windy season. Section 6 was made between the positions of sections 1 and 2 of April 1994 (Fig. 12). The upwelling was stronger in February 1998. Upper layer isotherms tilted more strongly and surface temperatures were about 23°C over the continental shelf. Salinities above 36.8 psu occurred at the coast and the 36.4 psu isohaline was lifted from 200 m depth to the surface over the shelf edge. Geostrophic currents were similar to those seen previously. The westward surface coastal jet was centred on 12.8°N, 50 km off the coast with a maximum speed >0.5 m s\(^{-1}\). The eastward flow was >0.2 m s\(^{-1}\) at 200 m.

Section 7 (12°N, 72°W to 13°N, 73°W) made on 17 February 1998 crossed the zone where minimum temperature and maximum salinity had been detected during the 1994 campaign off the cape. The vertical distributions reflected similar behaviour, with stronger upwelling near the coast and sharply delineated temperature and salinity fronts. As before, a geostrophic westward surface jet along the front of >1 m s\(^{-1}\) and an eastward undercurrent of ~0.1 m s\(^{-1}\) were seen (Fig. 11e).

In November 1998, the area was examined again with 15 CTD stations (Fig. 1c) at a time of weak winds and upwelling. The most remarkable feature was that the upwelled water was overlaid by a well-delineated stream of warmer and fresher water in Sections 8, 9, 10 and 11 (Fig. 13). This plume of lighter water was also observed in the SST imagery (Figs. 5c and 5d). The geostrophic currents had the usual structure of a westward coastal jet (<0.35 m s\(^{-1}\)) and an eastward undercurrent (<0.05 m s\(^{-1}\)) at 200 m.

The alongshore geostrophic transport estimated in the Guajira upwelling was about 5 Sv averaged over the sections from near shore to 120 km and above 1200m depth. Ekman transport integrated over 1000 km alongshore provides a wind driven offshore transport value of 1 Sv in the surface layer. Transport in the filaments could not be estimated for lack of in situ observations, but is expected to account for a major proportion of total offshore transport.

5. Discussion

The variability of the Guajira Upwelling Region is strongly influenced by mesoscale activity in the form of filaments. A major focus of this study, the offshore boundary of the upwelling centre where filaments appear was sampled at different times under different seasonal forcings. The presence of filaments arising from either the Paraguaná or the Guajira Peninsulas was detected in every SST and colour image of 72 examined. Therefore, these seem to be recurrent features of the upwelling independent of the time of the year. In the 1994 cruise, the northern boundary of the upwelling was detected as a strong front extending westward. Remote sensing imagery has shown the upwelling front (in both ocean colour and SST) at various times of the year to have a basically zonal orientation parallel to shore, but interrupted by the filaments.

Filament structures have been documented in coastal regimes off California (Brink and Cowles, 1991), Portugal (Haynes et al., 1993), south-western Africa (Lutjeharms and Stockton, 1987), the Arabian Peninsula (Kriest and Mitzka, 1998; Elliott and Savidge, 1990), Chile (Thomas, 1998) and northwest Africa (Barton et al., 1998) during their respective upwelling seasons. They all seem similar to the Guajira system in some aspects, although their development has been attributed to a variety of different causes.

Filaments grow at Paraguaná Peninsula and extend offshore for up to 400 km. At least occasionally, the external end of the filament rotates cyclonically and sometimes breaks away.
shedding a cyclone that then drifts independently away (Fig. 5). This eddy could either be produced by the filament or the filament entrained around a passing cyclone. The filaments are distorted by mesoscale eddies and meanders that are advected by the Caribbean Current, as in Andrade and Barton (2000). Anticyclonic meanders also can draw recently upwelled water away from the coast, creating long and thin filaments, as seen in the satellite images. The westward coastal upwelling jet along the South American coast could provoke current instabilities near capes, and thus expel water off the continental shelf to form the filaments. There is still insufficient data to favour any one of the conceptual models proposed by Strub et al. (1991).

An independent mechanism for nutrient enrichment is the Aeolian transport of sand. Wind blowing over the deserts of Guajira can transport significant amounts of sand to deposit them on the sea surface in the upwelling area, as was observed from space photography (Fig. 14a). Similar examples occur in eastern boundary currents like Baja California, where ‘Santa’ winds blow dust down narrow canyons out over the upwelling waters (Trasviña et al., 2003) and northwest Africa (Parrilla et al., 2002), where Saharan dust clouds deposit vast quantities of material to the ocean. The direct effects of such deposition remain little investigated.

Observations and imagery made along the seaward border of the upwelling region off Cabo de la Vela showed that cool upwelled water was disturbed by the presence of a well-delimited nearshore plume of brownish, warm and fresh water, reaching 50m depth (Fig. 14b, c). This plume is made up of the waters discharged from Lake Maracaibo to the Calabozo Bight in the Gulf of Venezuela. River waters in the Gulf of Venezuela turn west and remain in Calabozo Bight until their gradual entrainment into the coastal jet close to the Guajira Peninsula. This could be another mechanism for nutrient enrichment of water in this region. By the same means, hazardous materials from the oil industry may reach the upwelling area.

CZCS images suggest that the coastal waters just offshore Guajira have the highest concentrations of phytoplankton biomass year round. The more productive waters are limited to the “cool pool” or upwelling centre formed over the western Guajira, restricting the biomass to the waters above the continental shelf, except where it is advected offshore by the filaments. Maximum surface values of about 3 mg m\(^{-3}\) Chl-a are comparable with those found by Corredor (1979) in deeper waters which means that the upwelling here may have higher levels of productivity than previously thought. However Corredor concluded that the phytoplankton growth stimulated by inorganic nutrient enrichment off Guajira was significantly lower (by one order of magnitude) than in other eastern boundary upwelling ecosystems. He attributed this to the impoverished (oligotrophic) nature of the Subtropical Underwater that is upwelled.

This study also implies significant export of the nutrient-rich waters from the shelf. The role of upwelling filaments in transporting nutrients offshore may represent a significant loss. For example, nutrient-rich waters over the continental shelf in the upwelling season are likely to be swept rapidly westward or northward in the forming coastal upwelling filaments. Sometimes filaments form cyclonic eddies connected with the upwelling centre as was observed in SST and colour. These may separate and travel with the Caribbean Current bringing the upwelling waters further west.

Similar spreading of the larvae and eggs produced in the upwelling system likely has major implications for the distribution of species within the Caribbean. The persistent occurrence of filaments provides a mechanism for some planktonic organisms to leave the Guajira continental margin and subsequently to develop on the Central American coast or the banks in the Central American Rise. In contrast, others located in the mid-upper water column over
the central continental shelf will remain within the cyclonic circulation in the upwelling centre. This retention would provide an increased opportunity for those organisms to successfully grow in place.

9. Conclusions

The Guajira upwelling is an area of relatively high production because land intrudes into the LLJ core where atmospheric and oceanic flows are strong, enhancing and enriching the upwelling. The system shows the typical features of coastal upwelling, favored by the local orientation of the coast parallel to the predominant winds.

An intense westward coastal jet, reaching speeds >1 m s\(^{-1}\) in the near-surface layer, and an eastward undercurrent over the continental slope, with speeds up to 0.2 m s\(^{-1}\) at 200 m depth, were found at three distinct times of year. The undercurrent seems to be part of a continuous stream along the South American coast in the Caribbean Sea reported by Andrade et al. (2003). At the western limit of the Guajira upwelling centre a weak return flow formed a possibly permanent cyclonic circulation located between the jet axis and the Guajira coast.

Filament structures, originating in the coastal upwelling east of Paraguaná, carried cool water of high chlorophyll concentration offshore from the eastern Guajira Upwelling Region to the Central Caribbean area. The coastal jet off the western Guajira also extended upwelled water westward from the peninsula to form large filaments. Enriched coastal waters can be expelled to the open ocean by means of these filaments.

Northward extending filaments were distorted by incident anticyclonic meanders or eddies advected westward off the Guajira coast. Cyclonic eddies also form from or interact with the filaments. These are observed to separate from the filaments and travel with the Caribbean Current transporting the upwelled water hundreds of kilometres from their source. There was no indication of a return path to the coast for waters transported offshore in the filaments other than eventual recirculation through the South Western Caribbean gyre and coastal countercurrent.

There was no distinctive difference in the behaviour of the upwelling system between the three cruises in terms of the westward surface coastal jet, the eastward undercurrent and filament development. This suggests these phenomena exist through most of the year although the upwelling varied with the winds, strongest in January-March and weakest in November-December.

Both nutrient-rich, freshwater influence from the Gulf of Venezuela and Aeolian transport of dust from the adjacent Guajira desert can potentially affect conditions in the upwelling zone. As yet no direct observations or assessment of their interaction with the upwelling have been made.

The results demonstrate the existence of strong spatial variability in the upwelling circulation off the Guajira coast. Understanding the processes that lead to and control this spatial variability is critical to assessing the influence of ocean circulation on biological productivity and the transport of biogeochemical and anthropogenic material to and from the Guajira continental shelf.
References


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Figure Legends

Figure 1. Geographical location of CTD stations made during a) April 1994, b) February 1998 and c) November 1998.

Figure 2. SST from AVHRR image of 12 March 1998. At least 4 filaments are seen in the upwelling zones along the South American coast, including those off Guajira and Margarita Island. Grey areas indicate cloud.

Figure 3. Mean sea surface temperature from NOAA World Ocean Data (1994) showing the persistence of the Guajira upwelling system throughout the year. Maximum contrast occurs in February during the windy season. Dotted line marks the 72°W transect shown in Fig. 4a and b. Dot at 12.5°N 72°W marks the position of data shown in Fig. 4c.

Figure 4. a) Surface winds and b) Sea surface temperature along 72°W (dotted line in Fig.2) from NCEP-NCAR Monthly Long-term Means (1968-1996) c) Mean vertical temperature distribution at 12.5°N-72°W from NOAA World Ocean Data (1994). Minimum SST occurs when the wind has a southward component and greater velocity. Maximum temperature stratification occurs in October together with a general surface warming and weakest wind. The periods of the cruises are shaded in grey.

Figure 5. Sea surface temperature from AVHRR imagery in January 1998. Filament A was advected westward by the Caribbean Current. A plume of warmer water exits the western side of the Gulf of Venezuela and intrudes into the cooler upwelled water. The circled cyclone labelled ‘C’ separated from the filament. Its cooler SST signature is largely obscured in b) and d) by cloud or missing data (grey), but it can also be traced in altimetry (see text and Fig. 8).

Figure 6. Sea surface temperature from AVHRR imagery in March 1998. The sequence shows filament B originating from the Paraguaná peninsula. It extended from the upwelling to the northwest at a speed of about 0.15 m s⁻¹. The base of the filament migrated westward slowly. Grey areas are clouds/unavailable data.

Figure 7. AVHRR sea surface temperature in the Guajira region during a) The mid summer dry season and b) the beginning of the rainy season showing widespread warming. On 5 July 1997 a filament extended west from the Guajira region to the Southwest Caribbean Sea and one northward (image courtesy of P. Castellano, CARIACO). On 1 August 1998 the area was considerably warmer and one filament extended northward. Colour images of c) CZCS composite (courtesy of P. Clemente-Colon, NASA-GFSC) and d) SeaWIFS low resolution show significant amounts of chlorophyll embedded in the filaments being expelled from the upwelling area.

Figure 8. Sea level anomaly (cm) extracted from TOPEX-POSEIDON/ERS-2 analysis made at CCAR for Jan 1 - Mar 29 1998. The sequence shows the formation and evolution of cyclone C, from the upwelling filament produced in the Guajira region. The cyclone (see also Fig. 5) travelled north-northwestward arriving to Jamaica 100 days later.

Figure 9. Surface distribution of a) temperature b) salinity and c) dynamic topography referenced to 1200dbar, during April 1994. The pool of cooler, saltier water produced by the
upwelling occupied the Guajira shelf. The coastal jet centred on 13°N extended westward, but part recirculated eastward near shore.

Figure 10. Section 2 (72°W) in the Guajira region in April 1994 a) temperature b) salinity c) sigma-t and d) geostrophic velocity. The coastal upwelling is observed by the lifting of the isolines in the first 100m. A geostrophic westward near-surface jet with maximum speeds close to 1.5m.s⁻¹ and a slow sub-surface eastward counter-flow centred at 200m are seen.

Figure 11. Geostrophic velocities along meridional sections shown in Fig. 1. All sections showed the presence of a surface westward motion, a coastal jet offshore and an eastward underwater flow centred at 200m, with speeds up to 0.3m.s⁻¹.

Figure 12. Section 6 made along 71.8°W in February 1998 a) temperature b) salinity c) sigma-t and d) geostrophic velocity. This section is very similar to the previous ones measured in 1994; the upwelling is restricted to within 40km of the coast. The coastal jet has velocities above 1m.s⁻¹ and the eastward undercurrent extends 70km off the coast with velocities up to 0.2m.s⁻¹.

Figure 13. Temperature and salinity CTD sections 8-11 (see Fig. 1c) measured in November 1998 reveal a plume of warmer, fresher water intruding into the upwelling system. The geostrophic velocity profile between stations 1 and 2 shows the eastward underflow beneath the westward jet.

Figure 14. a) Photograph taken from SKYLAB over the Peninsula of Paraguaná showing the dust blown over the upwelled waters b) detail of the image in Fig. 5c showing the warmer waters flowing north from Lake Maracaibo being entrained into the upwelling area c) photograph of the fresh water plume front off the Guajira Peninsula.
Figure 1. Geographical location of CTD stations made during a) April 1994, b) February 1998 and c) November 1998.
Figure 2. SST from AVHRR image of 12 March 1998. At least 4 filaments are seen in the upwelling zones along the South American coast, including those off Guajira and Margarita Island. Grey areas indicate cloud.
Figure 3. Mean sea surface temperature from *NOAA World Ocean Data (1994)* showing the persistence of the Guajira upwelling system throughout the year. Maximum contrast occurs in February during the windy season. Dotted line marks the 72°W transect shown in Fig. 4a and b. Dot at 12.5°N 72°W marks the position of data shown in Fig. 4c.
Figure 4. a) Surface winds and b) Sea surface temperature along 72°W (dotted line in Fig.2) from NCEP-NCAR Monthly Long-term Means (1968-1996) c) Mean vertical temperature distribution at 12.5°N-72°W from NOAA World Ocean Data (1994). Minimum SST occurs when the wind has a southward component and greater velocity. Maximum temperature stratification occurs in October together with a general surface warming and weakest wind. The periods of the cruises are shaded in grey.
Figure 5. Sea surface temperature from AVHRR imagery in January 1998. Filament A was advected westward by the Caribbean Current. A plume of warmer water exits the western side of the Gulf of Venezuela and intrudes into the cooler upwelled water. The circled cyclone labelled ‘C’ separated from the filament. Its cooler SST signature is largely obscured in b) and d) by cloud or missing data (grey), but it can also be traced in altimetry (see text and Fig. 8).
Figure 6. Sea surface temperature from AVHRR imagery in March 1998. The sequence shows filament B originating from the Paraguaná peninsula. It extended from the upwelling to the northwest at a speed of about 0.15 m.s\(^{-1}\). The base of the filament migrated westward slowly. Grey areas are clouds/unavailable data.
Figure 7. AVHRR sea surface temperature in the Guajira region during a) the mid summer dry season and b) the beginning of the rainy season showing widespread warming. On 5 July 1997 a filament extended west from the Guajira region to the Southwest Caribbean Sea and one northward (image courtesy of P. Castellano, CARIACO). On 1 August 1998 the area was considerably warmer and one filament extended northward. Colour images of c) CZCS composite (courtesy of P. Clemente-Colon, NASA-GFSC) and d) SeaWIFS low resolution show significant amounts of chlorophyll embedded in the filaments being expelled from the upwelling area.
Figure 8. Sea level anomaly (cm) extracted from TOPEX-POSEIDON/ERS-2 analysis made at CCAR for Jan 1 - Mar 29 1998. The sequence shows the formation and evolution of cyclone C, from the upwelling filament produced in the Guajira region. The cyclone (see also Fig. 5) travelled north-northwestward arriving to Jamaica 100 days later.
Figure 9. Surface distribution of a) temperature b) salinity and c) dynamic topography referenced to 1200dbar, during April 1994. The pool of cooler, saltier water produced by the upwelling occupied the Guajira shelf. The coastal jet centred on 13\degree N extended westward, but part recirculated eastward near shore.
Figure 10. Section 2 (72°W) in the Guajira region in April 1994 a) temperature b) salinity c) sigma-t and d) geostrophic velocity. The coastal upwelling is observed by the lifting of the isolines in the first 100 m. A geostrophic westward near-surface jet with maximum speeds close to 1.5 m.s⁻¹ and a slow sub-surface eastward counter-flow centred at 200 m are seen.
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