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The southern Caribbean upwelling system: Sea surface temperature, wind forcing and chlorophyll concentration patterns

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ABSTRACT

Sixteen years of sea surface temperature (SST, 1994–2009) were used to characterize the southern Caribbean upwelling system. This system extends from 61–75.5°W and 10–12.5°N, with 21 upwelling foci clustered in seven groups differentiated by their SST cycles. Two of those groups had the strongest coastal upwelling: the 'eastern area' (63–65°W) and the 'western area' (70–73°W). The literature reports that the eastern and western upwelling areas hold 78% and 18% of the small pelagic biomass within the upwelling system, respectively. We looked into variations of the upwelling dynamics in those areas using seasonal cycles of satellite SST, chlorophyll-*a* (Chl) and sea-wind, as well as climatological hydrographic data from the World Ocean Atlas. Comparing their annual averages, the eastern area featured the lowest SST (25.24 °C) and the highest Chl (1.65 mg m^{-3}); it has moderate wind intensity (6.12 m s^{-1}) and shallower 22 °C isotherm (85 m). The western area had stronger winds (8.23 m s^{-1}) but deeper 22 °C isotherm (115 m), slightly higher SST (25.53 °C) and moderate Chl (1.15 mg m^{-3}). The upwelling in the eastern area was more prolonged than in the western area (SST $<$26 °C during 8.5 and 6.9 months, respectively). According to the 'optimal environmental window' theory, small clupeoid recruitment is a dome-shaped function of the upwelling intensity, turbulence and SST, with an optimum wind speed around 5–6 m s^{-1}. The eastern upwelling area wind speed is close to this optimum value. The western upwelling area shows much higher wind speed that causes high level of turbulence and strong offshore transport that could hinder small pelagics recruitment in that area.

1. Introduction

The southern Caribbean Sea (Fig. 1) experiences strong wind-driven coastal upwelling from approximately January to May along the continental margin, between about 61°W to 74°W and 10–13°N, along the coasts of Trinidad, Venezuela and Colombia (Richards, 1960; Herrera and Febres-Ortega, 1975; Muller-Karger and Aparicio, 1994; Andrade-Amaya, 2000; Castellanos et al., 2002; Muller-Karger et al., 2004; Ruiz-Ochoa et al., 2012). This upwelling process maintains a highly productive ecosystem in the region, hereafter called the southern Caribbean upwelling system. Four acoustic fisheries surveys were conducted during 1988 (during the four seasons) by the R/V Dr. Fridtjof Nansen on the shelf region from Suriname to the western border of the Colombian Caribbean (Stromme and Saetersdal, 1989). The total biomass of small pelagics in the southern Caribbean upwelling system was estimated at 1,580,000 metric tons, which includes clupeids, anchovies, carangid, scombrids and barracudas. Nearly all (95%) was concentrated in two areas, named henceforth the eastern and western upwelling areas (located at 63–65°W and 70–73°W, respectively). However, the eastern area had a much higher biomass of small pelagics (78%).

Satellite-derived sea surface temperature (SST) serves as a proxy for upwelling in this tropical region. Strong upwelling here occurs primarily during the northern hemisphere winter, but the southern continental margin of the Caribbean shows lower sea surface temperatures than surrounding waters year-round (Figs. 2 and 3). In the western Caribbean (~10°N and 76°W) SST had show high correlations with *in situ* temperature measured at 10 m depth (r=0.76, Ruiz-Ochoa et al., 2012). SST imagery from 1996 was used in the southern Caribbean to identify the location of upwelling centers with the cooler waters (or upwelling foci, Castellanos et al., 2002).

In this paper we characterized the upwelling foci along the southern Caribbean upwelling system using patterns observed in a longer SST time series (1994–2009). We compared the upwelling dynamic in the eastern and western upwelling areas to find out differences that could explain their disparity in fish resources. Regional differences in upwelled waters temperature were assessed studying the annual SST cycle for the southern Caribbean upwelling system. The response of the phytoplankton biomass to

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the seasonal changes of upwelling was also evaluated using satellite-derived chlorophyll-*a* concentration (Chl). The upwelling forcing due to the wind and the curl of the wind was calculated using satellite-based ocean wind observations. The seasonal cycles of SST, Chl and wind showed differences that could explain the disparity in biomass of small pelagics between these areas.

2. Methods

2.1. Sea surface temperature

To study the southern Caribbean upwelling system we defined a window bound by 8°–16°N, 77°–58°W. We used high resolution (1 km) sea surface temperature (SST) observations collected by the Advanced Very High Resolution Radiometer (AVHRR, National Oceanic and Atmospheric Administration/NOAA) and downloaded by a ground-based L-band antenna located at the University of South Florida (St. Petersburg, Florida, U.S.A.) This antenna collected between 15 and 30 AVHRR SST passes daily, allowing for high temporal coverage of the study region. SST was derived using the multi-channel sea surface temperature split-window techniques (Walton, 1988; Strong and McClain, 1984; McClain et al., 1983).

A cloud filter similar to that of Hu et al. (2009) was used to improve data quality. All daily values in the time series larger than 2 standard deviations above or 1.5 standard deviation below a weekly climatology were discarded. These values were selected by trial and error and work well for the tropical SSTs in the Caribbean Sea where the upwelled waters produce the coolest seasonal SST signal in the area. The filtered daily images were then used to calculate new weekly composites and a new long-term weekly climatology (January 1994–December 2009).

The internal Rossby radius (Mendo et al., 1989; R=square root [g $\Delta\rho/\rho$ h/f]) characterizes the cross-shelf scale of upwelling. The internal Rossby radius for this region is ~19 km; estimated using a mean depth h=35 m, gravity g=9.81 m s^{-2}, and adjusted by the ratio of local vertical density differences and the density ($\Delta\rho/\rho$: 0.9 kg m^{-3}/1025 kg m^{-3}) at the CARIACO time series between 0 and 35 m, and the coriolis value f=2.9 × 10^{-5} s^{-1}. Data from the CARIACO time series was downloaded from http://www.imars.usf.edu/CAR/.

Coastal SST time series were extracted from 172 points distributed along the coast, approximately 10 km from the coast from Trinidad to the central coast of Colombian Caribbean Sea (Fig. 2b). Each point represented an average of the SST in a 5 × 5 pixel box (~25 km^2) centered at each station.

To examine similarities in upwelling timing and intensity between different upwelling foci, we applied a hierarchical cluster analysis (Pang-Ning et al., 2005) to the SST time series extracted from each upwelling focus (boxes depicted in Fig. 3). For comparison, the analysis also included the SST time series from the central-eastern Caribbean Sea and from the northwestern equatorial Atlantic Ocean (sees locations in Fig. 1).

2.2. Chlorophyll-a

We used high resolution (1 km) satellite chlorophyll-*a* estimates (Chl; O'Reilly et al., 2000) from images collected with the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) for the period January 1998-December 2009. Data were downloaded for the study area from NASA (http://oceancolor.gsfc.nasa.gov/SeaWiFS/) and mapped to a uniform spatial grid using Matlab routines provided by NASA. Weekly Chl averages were calculated from January 1998 to December 2009. Because chlorophyll is approximately log-normally distributed, all calculations were made using log [Chl].

Riverine discharge can produce a very strong signal in the satellite derived Chl product because of high concentrations of CDOM (colored dissolved organic matter), leading to erroneously high estimates of pigment concentration (Carder et al., 1999). The southern/central Caribbean Sea is influenced by several large and small rivers. The Amazon, Orinoco, and Magdalena are the largest rivers affecting the Caribbean region, with the Orinoco and Magdalena discharging directly into the basin (Fig. 1). In order to separate the influence of upwelling from the freshwater discharge on Chl levels, we compared weekly SST and log[Chl] time series with a linear regression analysis (1998–2009). A weekly Chl climatology was calculated and the coastal values were extracted at the same 172 coastal stations used for SST (Fig. 2b) but using a 13 × 13 pixel box centered at each station to account for larger numbers of missing pixels in the Chl imagery compared to the SST data.

2.3. Wind

Synoptic surface ocean wind observations from the NASA QuikSCAT satellite for the period 1999–2009, gridded to a spatial resolution of 0.25°, were obtained from the Physical Oceanography Distributed Active Archive Center (PO.DAAC) at the NASA Jet Propulsion Laboratory. Away from coastal zones, scatterometer wind retrievals are estimated to be accurate to better than 2 m s^{-1} in speed and 20° in direction, similar to the accuracy of *in situ* buoy measurements (Freilich and Dunbar, 1999). Due to contamination

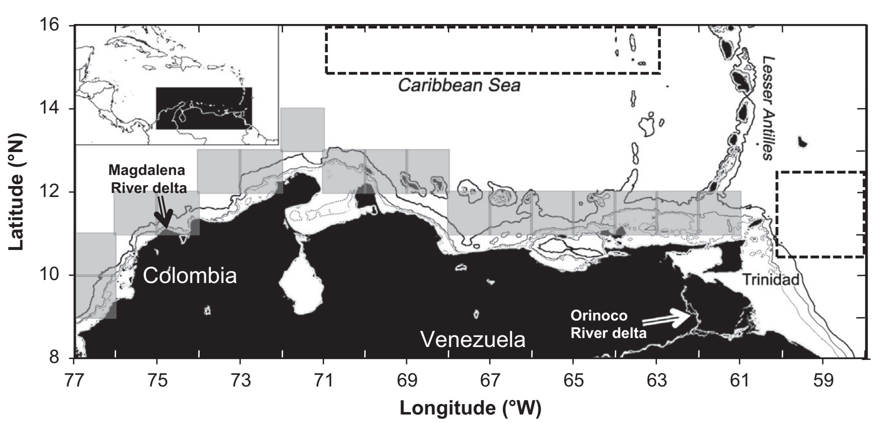

Fig. 1. Map of the study region (8–16°N and 58–77°W). The 100, 200 and 1000 m isobaths are shown in increasing shades of gray. SST data was extracted from the central-eastern Caribbean Sea (top dashed rectangle, 15–16°N and 63–71°W) and the northwestern equatorial Atlantic Ocean (right dashed rectangle, 10.5–12.5°N and 58–60°W). Gray squares mark areas where climatological temperature profiles were extracted from the 1 × 1 degree World Ocean Atlas 2005.