Characterization of Caribbean Meso-Scale Eddies

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LONG-TERM GOALS

Our long-term goal is to improve predictivity of physical, biogeochemical and optical properties of Eastern Caribbean waters under the influence of mesoscale eddies and their interaction with regional features (i.e. massive riverine discharge). Expected outcomes from this research include the capacity to infer susbsurface properties and processes as well as their temporal and spatial evolution utilizing remotely acquired surface observations. This program will contribute to the development of infrastructure for marine research and education at the University of Puerto Rico. A particular expectation is the recruitment and training of graduate students who will focus their graduate research in current scientific issues attuned with the above expressed goals.

SPECIFIC OBJECTIVES

- Describe/model the interaction of physical, chemical, biological and optical variables across fronts, eddy structures and massive river plume discharges in the Eastern Caribbean Sea.

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- Develop sub regional, empirical relationships between horizontal and vertical physical/biogeochemical gradients and remotely sensed ocean properties.

APPROACH

We have implemented a series of research cruises, code named CaVortEx (for Caribbean Vorticity Experiment) to carry out observations of the optical and physical structure and upper water column biogeochemistry of mesoscale eddies. Eddy distribution and displacement were followed using the output from 1/16^{o} operational global Naval Research Laboratory (NRL) Layered Ocean Model (NLOM), near real time altimetry data, SeaWiFS and MODIS imagery. During research cruises we obtained continuous flow surface records of temperature (T), salinity (S) and chlorophyll a (Chl-a), vertical sections of these variables plus apparent optical properties using the Nν-shuttle underwater undulating towed data acquisition system. Discrete vertical profiles of physical (T, S), chemical (dissolved oxygen, nutrients, colored dissolved organic matter and inherent (a, b, c) and apparent (R, R_{RS}, T, K_z) optical properties were obtained. Current structure across fronts and eddies was characterized by means of ship-lowered (LADCP) current profiler. These studies also included assessment of rates of biomass accumulation, primary production and photosynthetic efficiency using radiocarbon incubations on-deck to determine photosynthetic parameters and fast repetition rate fluorometry (FRRF) in situ.

WORK COMPLETED

A synthesis of work to date on this program, with emphasis on the physical oceanography of the Eastern Caribbean Sea eddy field structure was presented in the 2006 Ocean Sciences Meeting in Hawaii (Lopez et al 2006). Two peer reviewed papers were completed. The first explores thermohaline staircases in a Caribbean eddy and mechanisms for staircase formation Morell et a. l(2006a). The second, Morell et al. (2006b in review), presents an analysis of the interaction of eddies with the Orinoco/Amazon freshwater plume in the Eastern Caribbean incorporating in situ vertical light attenuation coefficient (Kd490) measurements as well as estimates from MODIS and SeaWiFS imagery. Also, in FY 06, two cruises were completed to document the optical, physical, chemical and biological properties of contrasting water masses across eddy boundaries and to characterize the biogeochemical transformations arising from boundary interactions. These were designed to test model results which indicate that, under the influence of meso-scale eddies, primary frontal boundaries undergo spatial modifications resulting in enhancement of vertical and horizontal flux, and of biogeochemical activity and that “eddy pumping” similarly results in enhanced biological production. Such interactions generate variability of inherent optical properties in response to changes in particle abundance and size distribution resulting from enhanced biological production, phytoplankton community successions, and increased release, production and transformation of CDOM.

RESULTS

A. Thermohaline staircases in a Caribbean eddy

The structure of a cyclonic eddy in the eastern Caribbean was observed by Caribbean Vorticity Experiment cruise CaVortEx I in August 2003. Prominent thermohaline staircases are evident in profiles of temperature and salinity at locations that appear to correlate with the presence of lateral property gradients and shear within the eddy, although such a connection is less than definitive due to the coarseness of horizontal sampling. In this paper, the CaVortEx I staircase observations are examined in greater detail. Because the observed heterogeneity of step properties with horizontal location and depth potentially provides clues as to the conditions under which staircases form, the observations are analyzed in the context of two proposed scenarios for staircase formation, that staircases arise through the growth of double diffusive intrusions and that staircases arise through an instability of the vertical flux-gradient relations for salt fingering. The former mechanism requires lateral T and S gradients to operate, whereas the latter can occur under laterally uniform conditions. Aspects of the data are found to be consistent with each, raising the possibility that both mechanisms are operating.

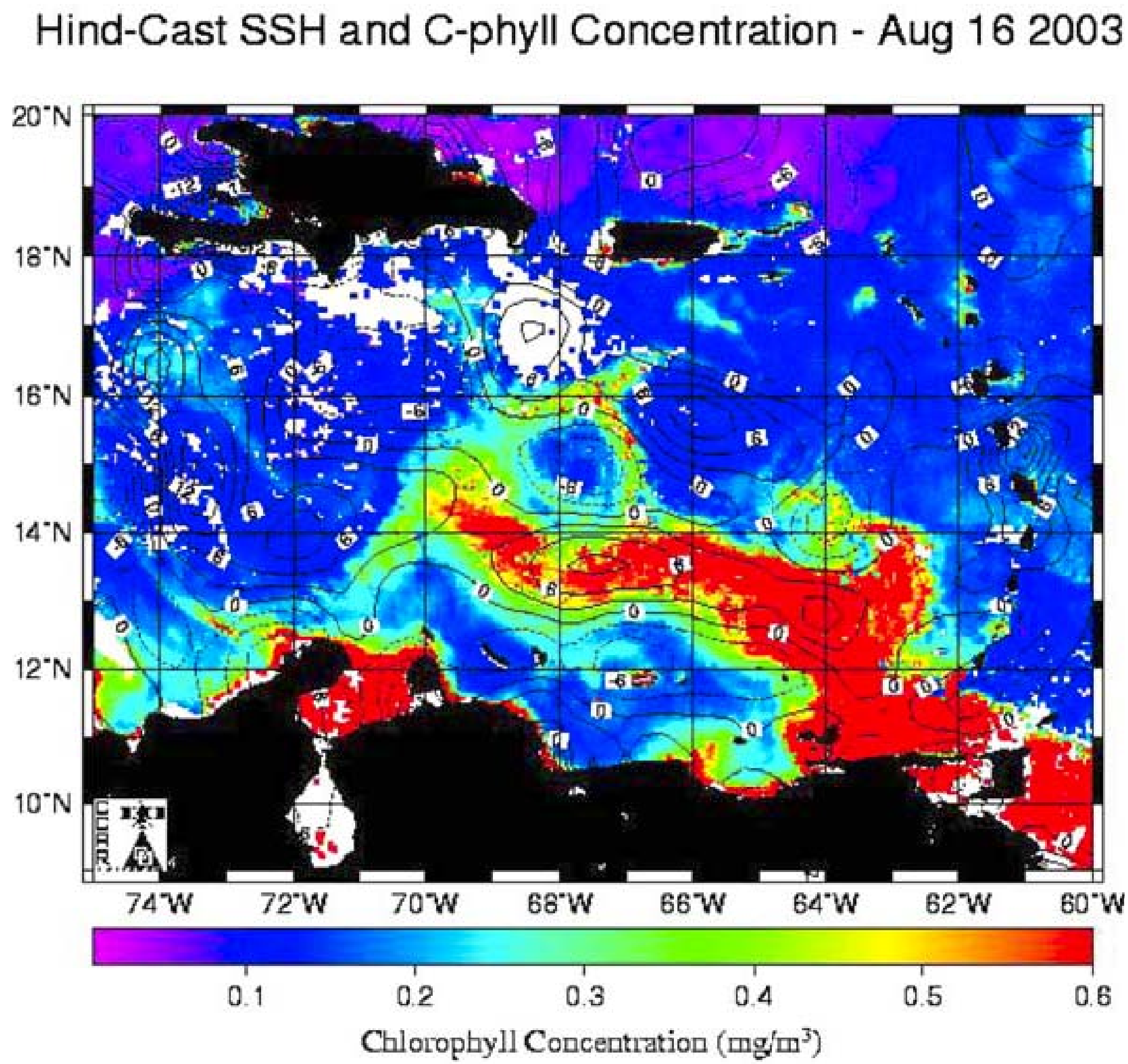

Fig. 1. Chlorophyll concentration (colors) and sea-surface height anomalies (contours labeled in cm) in the eastern Caribbean on August 16, 2003. The center of the cyclonic eddy traversed during CaVortEx I lies in the near 15N, 67'500W in a region of negative sea-surface height anomaly. The Orinoco River plume corresponds to the large region of elevated chlorophyll concentration lying mainly southward and eastward of the eddy. (Image obtained from the Colorado Center for Astrodynamics Research at the University of Colorado, Boulder.)

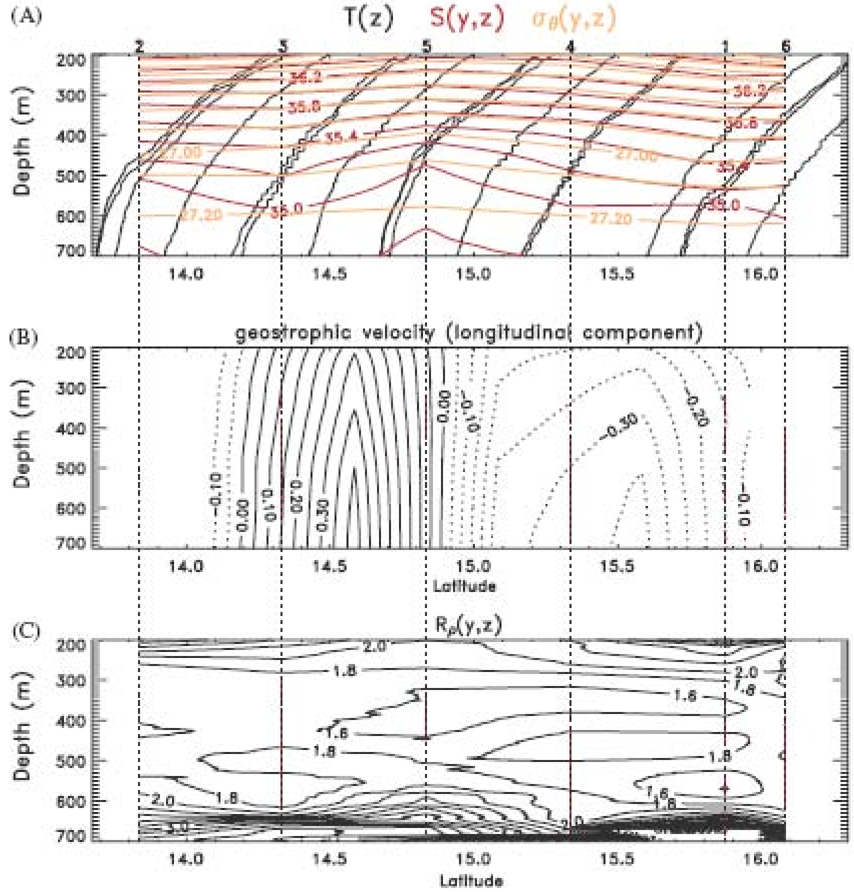

Fig. 2. (A) T versus depth from CTD measurements (thick black curves) and XBT casts (thin black curves). Traces are plotted on an arbitrary scale, and are offset from each other by distances proportional to the latitudinal spacing between stations. Red contours denote isohalines and orange curves isopycnals, both smoothed vertically by a 61-m running mean. (B) Contours of longitudinal geostrophic velocity. (C) Contours of density ratio, Rr, smoothed vertically by a 61-m running mean. In (B) and (C), approximate depth ranges containing steps (intrusions) are marked by thick (thin) vertical bars. The vertical dotted lines denote loci of CTD stations, identified above the top panel.

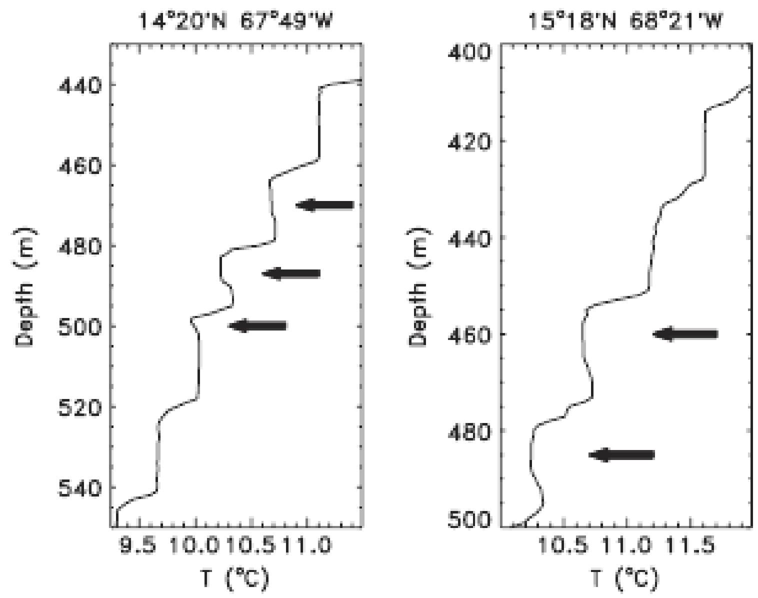

Fig. 3 Temperature as a function of depth at two of the CaVortEx I CTD stations, showing intrusion-like inversions within some steps (arrows).

B. Analysis of Eddies Interaction With Massive River Plumes

Optical properties of near-surface waters of the Eastern Caribbean Basin are strongly modulated by two prevalent features: river plumes and meso-scale eddies. This manuscript describes how a meridional gradient of near-surface diffuse attenuation of downwelling irradiance (Kd) prevails in the Eastern Caribbean Basin (ECB) with high values near South America and progressively lower values across the ECB into the adjacent north Atlantic Ocean.

Light attenuation at shorter wavelengths is attributable principally to absorption by CDOM transported in the Orinoco and Amazon River plumes; phytoplankton absorption becomes dominant only along fronts between buoyant river plumes and higher density oceanic waters. Vertical attenuation profiles at lower wavelengths (Kd412) in the southeastern Caribbean basin show a stratified structure with higher values in surface layers and increasingly lower values at depth, approaching those of near surface waters of the central North Atlantic gyre. Fall climatological satellite-derived near-surface Kd490 values for the region correlate well to our in situ measurements.

We found that meso-scale eddies modulate the optical nature of near-surface waters by either entraining or displacing the optically shallow river plume waters resulting in diverse scenarios including "cat eye" spiral structures, optically clear patches of oceanic water embedded in the river plumes, and optically shallow lenses of river plume waters advected into the optically clear oceanic water masses. Mesoscale eddies both steer and stir the river plume on time-scales of weeks to months. Satellite-derived Kd products reflect well the long-term climatological optical structure but time-averaging to reduce cloud cover data loss degrades the imaging of dynamic features such as mesoscale eddies.

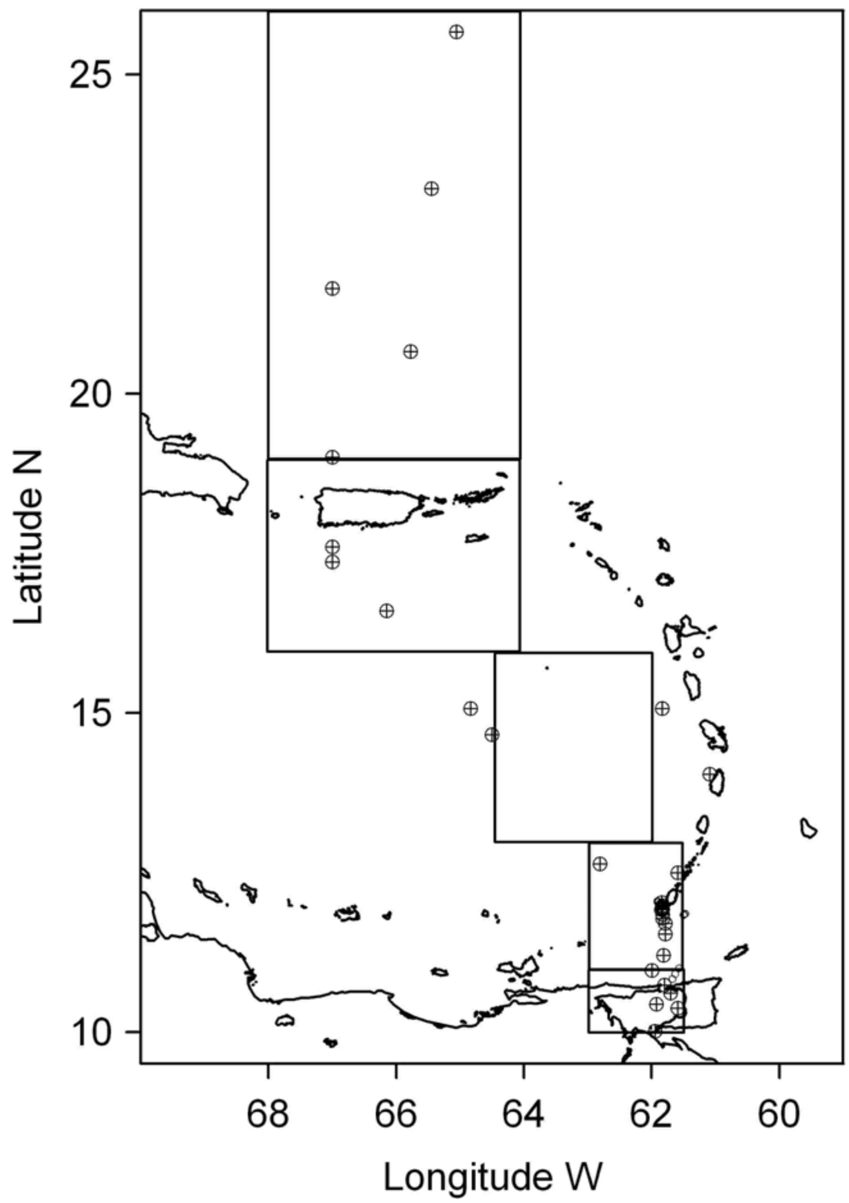

Figure 4. Map of the ECB depicting oceanographic sampling stations. Boxes indicate sub-regions selected for analysis of satellite remote sensing products.

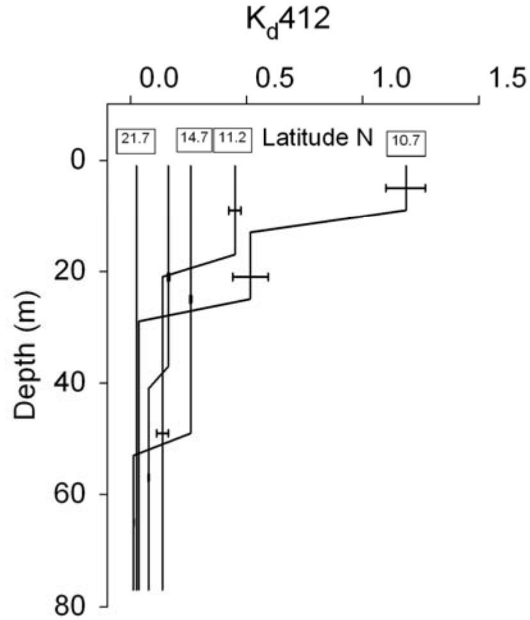

Figure 5. Representative vertical profiles for Kd412 across the latitudinal gradient. Kd412 values in the river plume at low latitudes are high but values at depth below the plume approach the near-surface values of oceanic waters at higher latitudes.

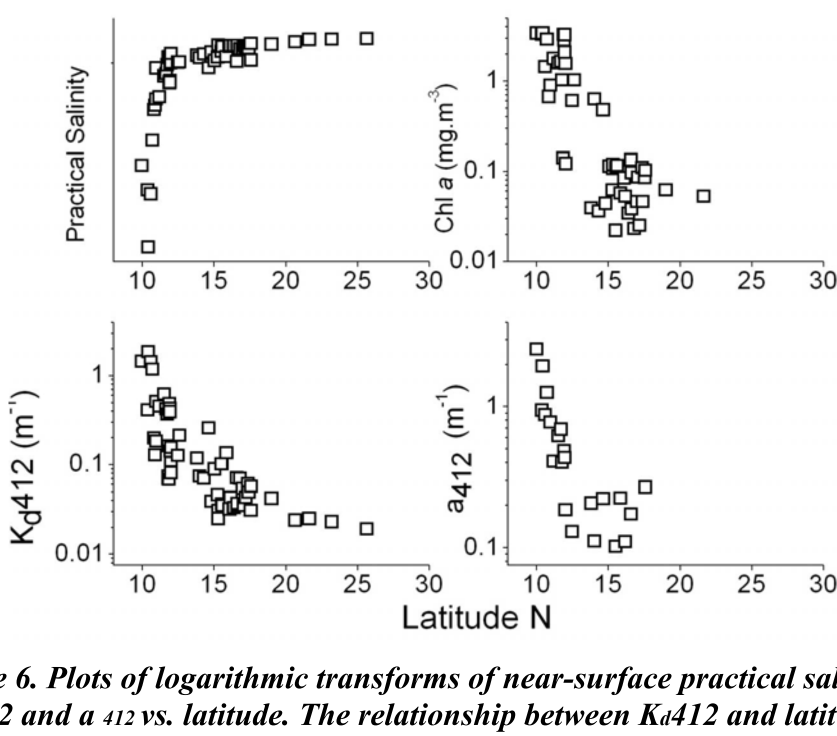

Figure 6. Plots of logarithmic transforms of near-surface practical salinity, Chl a, K_d412 and a $_{412}$ vs. latitude. The relationship between K_d412 and latitude can be described by an exponential decay function (r^2 = 0.62; n = 60).

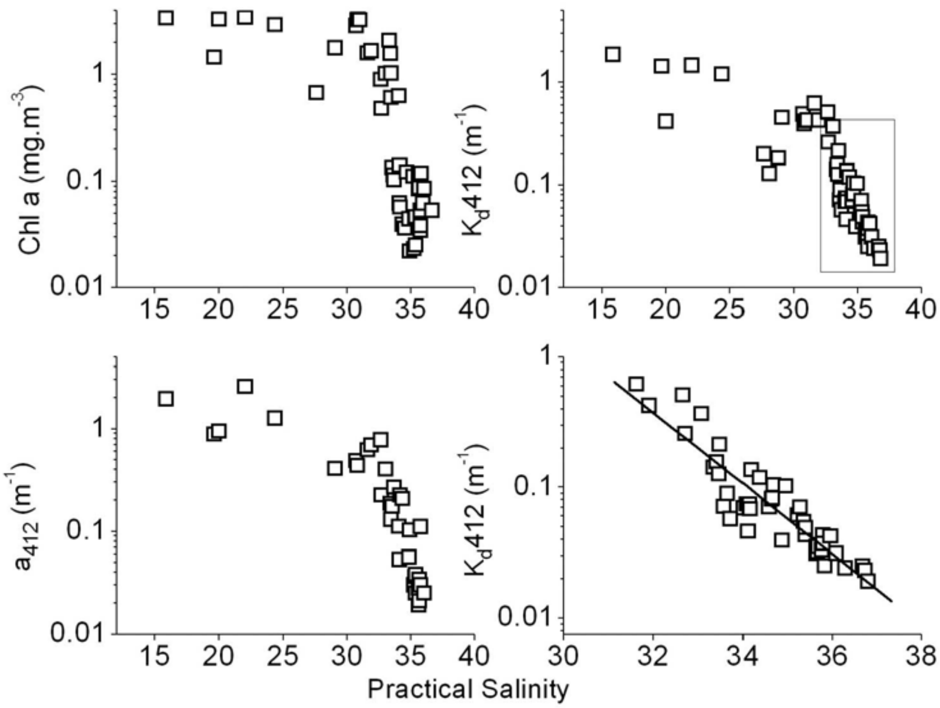

Figure 7. Plots of logarithmic transforms of near-surface Chl a, Kd412 and a 412 vs. practical salinity. A subset of the data in the top right panel, denoted by the box, consists of values above practical salinity 30, is plotted in the lower right panel. The relationship between salinity and Kd412 in this salinity range adjusts well to an exponential decay function (r^2 = 0.85; n = 44) denoting loss of CDOM beyond dilution and attributable to photodegradation.

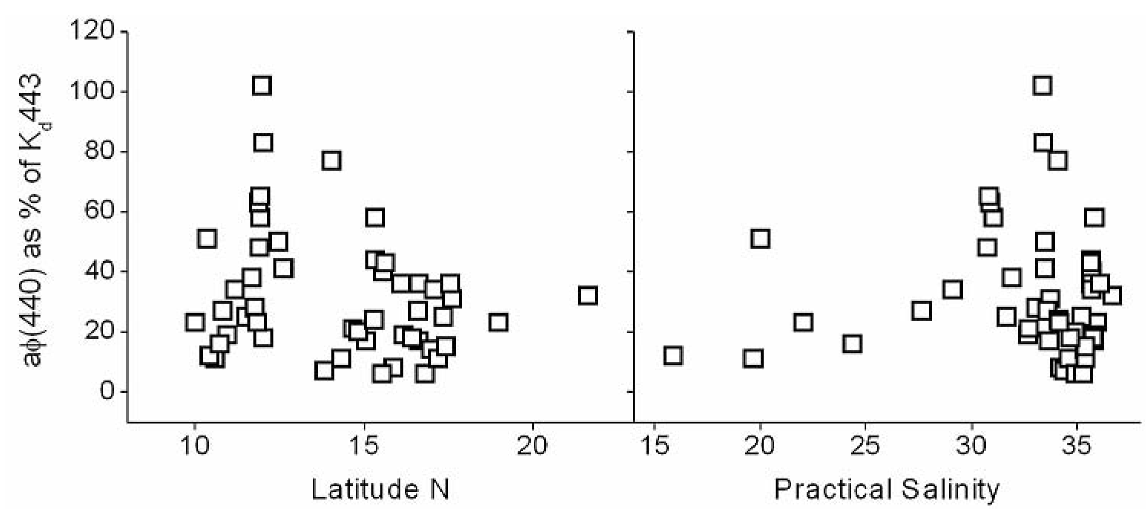

Figure 8. Plots of phytoplankton absorption at 440 nm, computed from our in situ Chl a values and the expression of Bricaud et al. (2004), vs. latitude (left) and salinity (right).

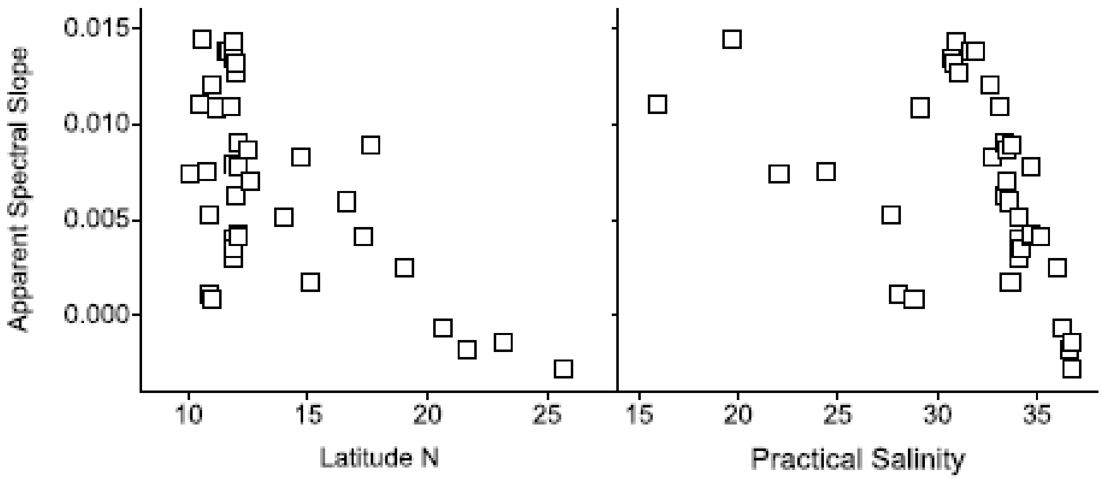

Figure 9. Plot of apparent spectral slope (SA) vs. latitude (left) and salinity (right). The linear decay of SA with salinity reflects CDOM photodegradation.

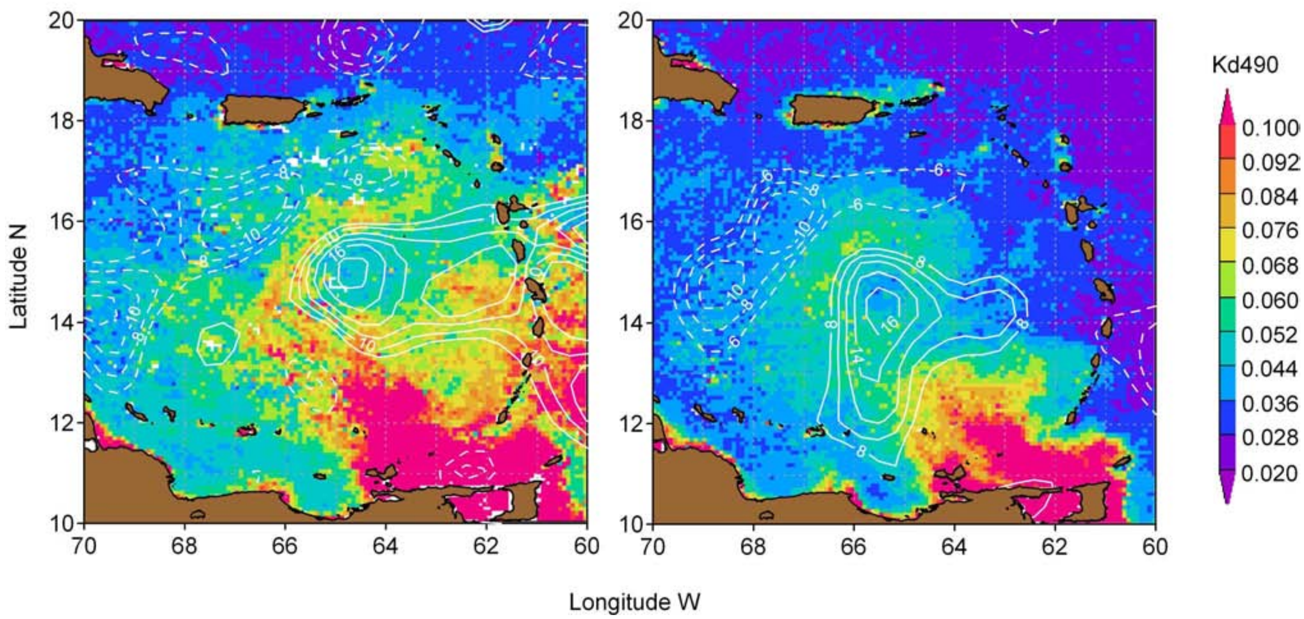

Figure 10. Satellite derived images of Kd490 (m-1) distribution in the ECB with a Sea Surface Height Anomaly (SSHA) (cm) overlay depicting eddy-plume interactions. Left: June 2002. Right: December 2003. River plume trajectory is constrained by eddy size and rotational direction.

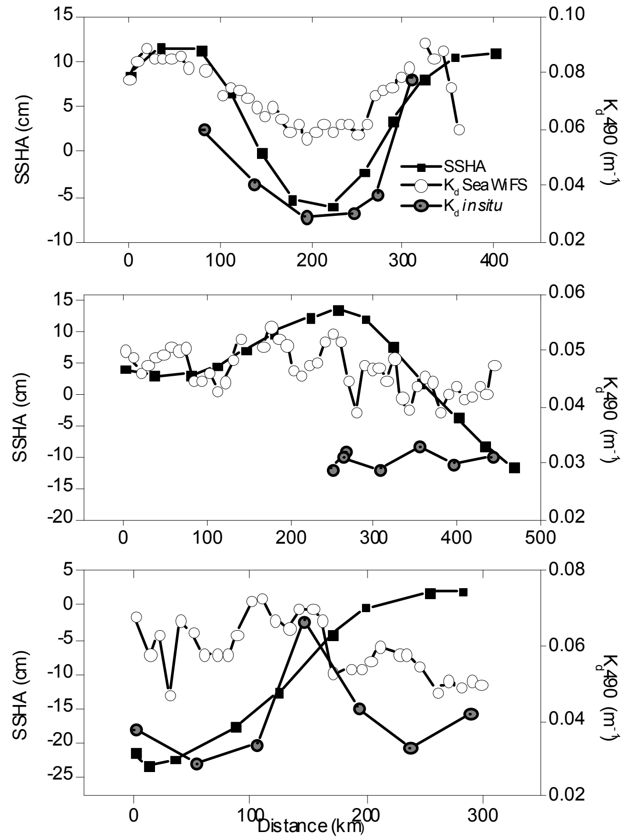

Figure 11. Plots of SSHA from AVISO 7 day composites of multiple satellites (black), SeaWiFS K_d490 from level 3, 9 km resolution weekly composites (white) and in situ K_d490 (gray) across: (top) a cyclonic eddy in the ECB. SSHA 16 August 2003, SeaWiFS K_d490 13- 20 August 2003 both along 67° W longitude, in situ data 16 – 19 August 2003 along 67.8° W.; (middle) an eddy pair in the ECB: in situ data along a transect from 16° 10' N 67° 15' W to 17° 25' N 64° 52' W June 22-25 2004; SSHA 23 June 2004, SeaWiFS K_d490 17 – 24 June 2004 and (bottom) an anti-cylonic eddy in the central Caribbean basin; in situ data March 15-17 2005 along 74° 30'W; SSHA March 19 2005 SeaWiFS K_d490 March 2005.

Conclusions

Optical properties of the ECB are strongly modulated by the discharge of the Amazon and Orinoco Rivers. The plumes of these rivers form shallow buoyant lenses of high light attenuation overlying optically clear oceanic waters. Near-surface vertical light attenuation shows exponential decay of the signal along the ORP dispersal axis. CDOM absorption at shorter wavelengths generally prevails throughout the plume. Phytoplankton absorption is the main contributor to light attenuation only along a narrow latitudinal fringe coincident with abrupt changes in water properties. In our study, the sum of spectrophotometrically measured a_{412} and modelled a usually exceeded radiometrically measured K_d412. Likely biases denying closure include variability of in situ measurements related to solar angle [Stramska and Frye, 1997] and our instrumental limitations for assessing attenuation coefficients in the critical surface range (<5m) of the buoyant plume. Non-linearity of K_d412 with regard to salinity evidences CDOM photodegradation in plume waters at practical salinities greater than 30. Our observations support previous arguments that current algorithms based on satellite ocean-color measurements result in overestimates of near-surface Chl a concentration in this region. Moreover, dilution and photochemical CDOM decay, as the plume spreads and ages, complicate development of more robust algorithms.

Remote sensing adequately portrays climatological distribution of vertical diffuse attenuation but currently available monthly averaged imagery of near-surface K_d490 blurs dynamic interactions between eddies and plume waters. Eddies interacting with the river plumes thus bring about significant deviations from the climatology. Finally, sparse coverage of radar altimetry and the resulting need for time-averaging of multiple satellite passes further compound the difficulty of accurately portraying the influence of dynamic meso-scale phenomena on ocean color.

C. CaVortEx 5 Oceanographic Cruise

The oceanographic cruise CaVortEx 5 was conducted in the eastern Caribbean during the second half of the month of November 2005. The main objectives were to examine the Orinoco's river plume evolution and mesoscale eddies across the Eastern Caribbean. Three legs comprised this cruise: the first leg departed from Puerto Rico and arrived at Trinidad, the second leg departed from Trinidad and arrived at St Lucia, and the third leg departed from St. Lucia and arrived at Puerto Rico. The task during the second leg was to estimate currents using an LADCP (Lowered Acoustic Doppler Current Profiler). The LADCP (600 kHz RD Instruments) collects stratified velocity vectors from the water column. Its sensitivity range is grossly 100m, but it is lowered on a rosette, sampling a larger volume. The physical data associated with the mesoscale eddies were collected during the third leg, from St. Lucia to Puerto Rico, using LADCP and XBTs data.

Data collected during the third leg was associated with a mesoscale eddy in eastern Caribbean. Stations were occupied during November 26 and 27, 2005. An anticyclonic eddy was suggested south of Saint Croix during this leg. Physical data collected included LADCP casts and XBT's profiles.

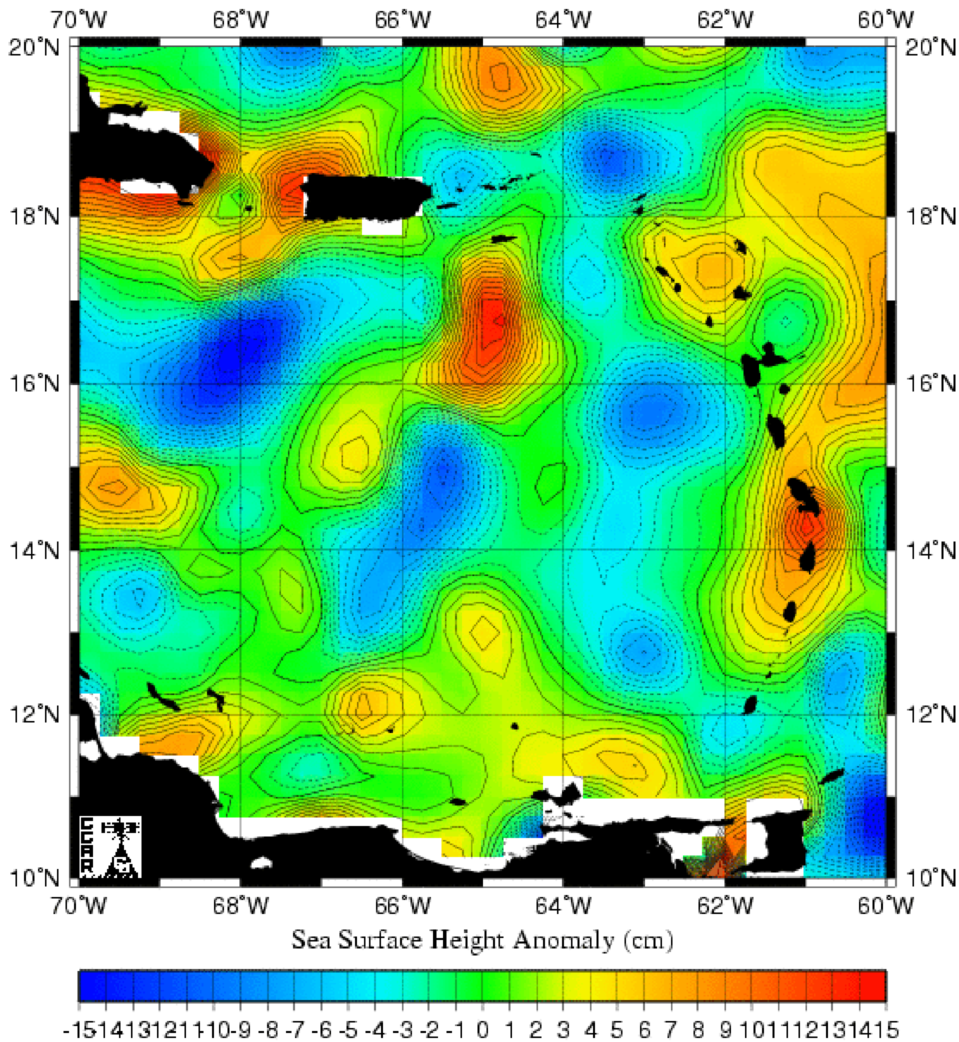

Figure 12. Sea surface height anomaly satellite image during November 24, 2005.

Results

To visualize physical features produced due to the eddy influence, 18°C and 22°C isotherm contour plots were prepared from the XBT casts (Fig 2 and Fig 3).

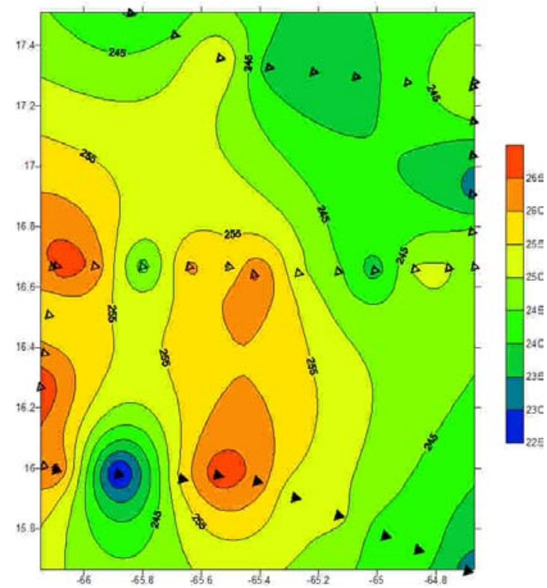

Fig 12. Cvtx 5: XBT 18°C Topography

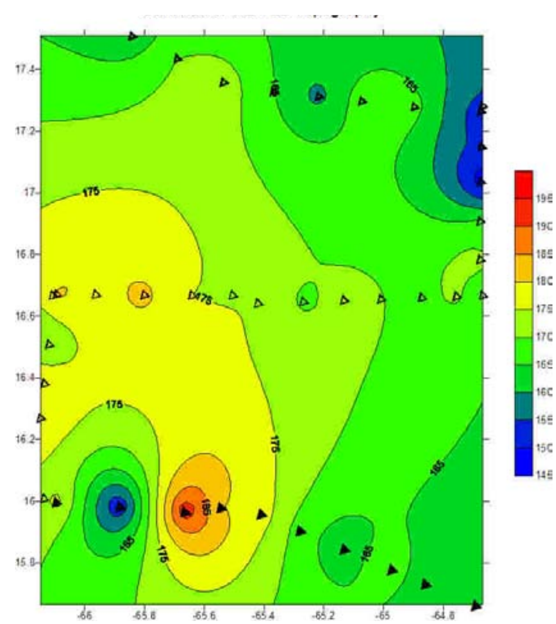

Fig 13. Cvtx 5: XBT 22°C Topography

The first XBTs were bias by an instrument electric malfunction producing spikes in the temperature profile. Additional contours were produced using only "good" XBTs and instead of using the isotherms, anomalies were calculated for specific depths (90m and 450m) (Fig 14 and 15). An isotherm contour was obtained along a meridian transect at the 16.6°N latitude (Fig 16).

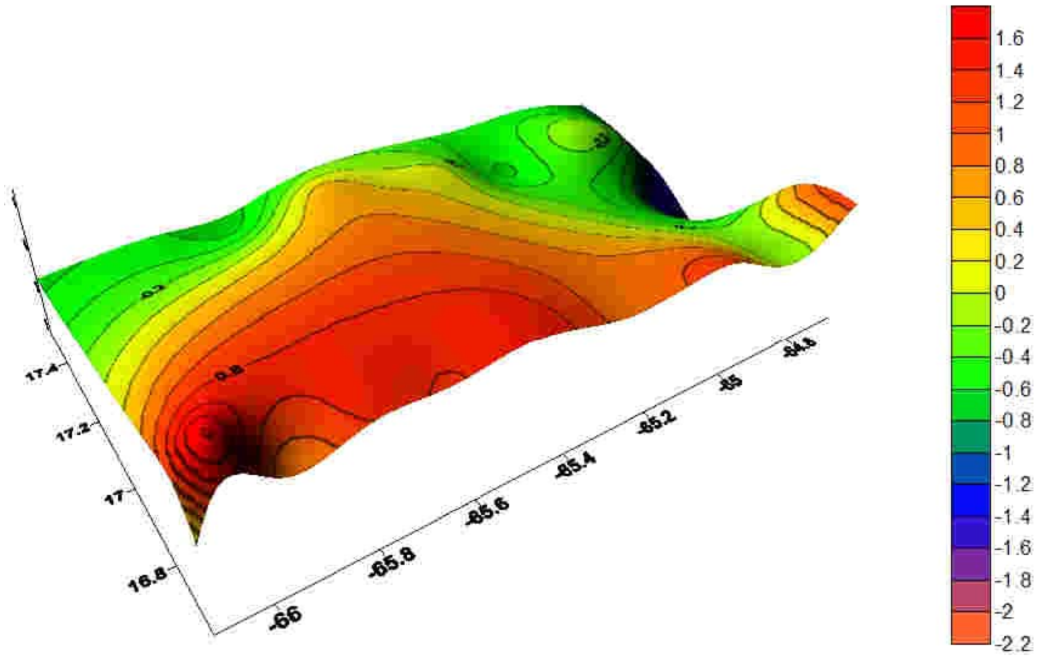

Figure 14. Cvtx temperature anomalies at 90 m.

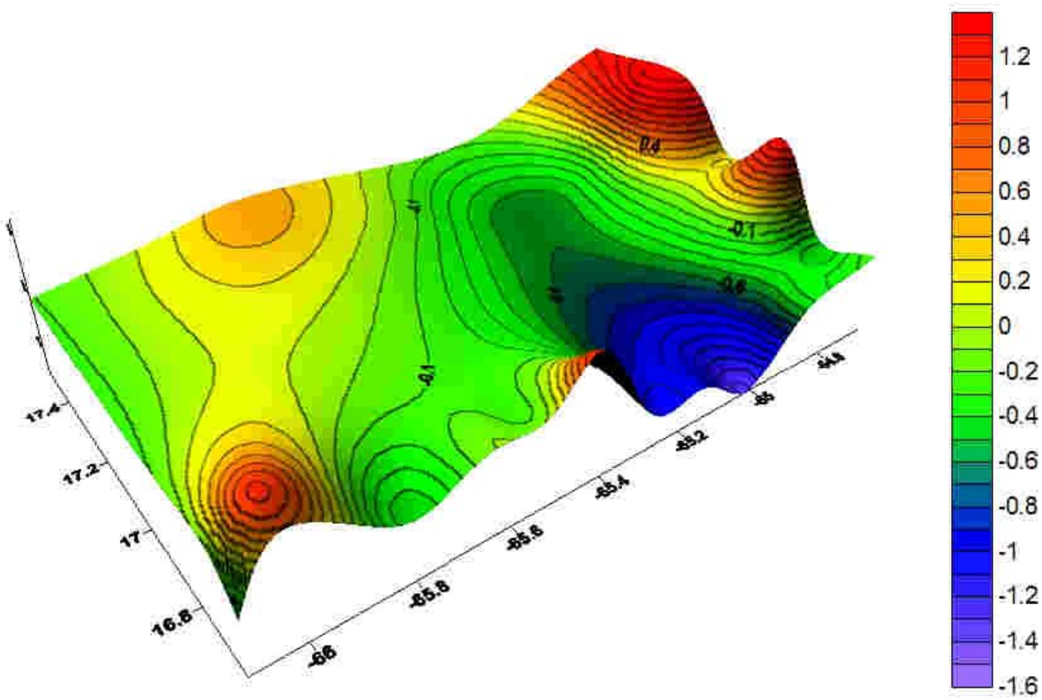

Figure 15. Cvtx temperature anomalies at 450 m.

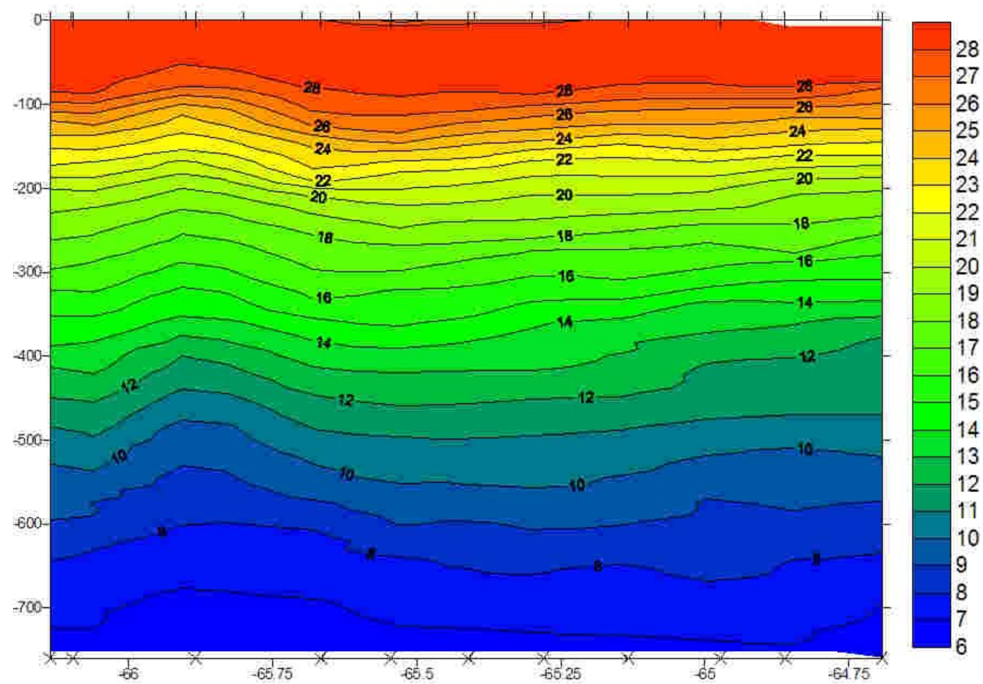

Figure 16. Temperature isoclines contour along a meridian transect at 16.6°N.

A complex regime of current profiles, influenced by strong winds at surface and the Atlantic/Caribbean transport, was obtained suggesting baroclinicity in the water column (Fig. 17). Alternatively, a recent blue shift from a large eddy crossing through the Lesser Antilles passage could be occurring.

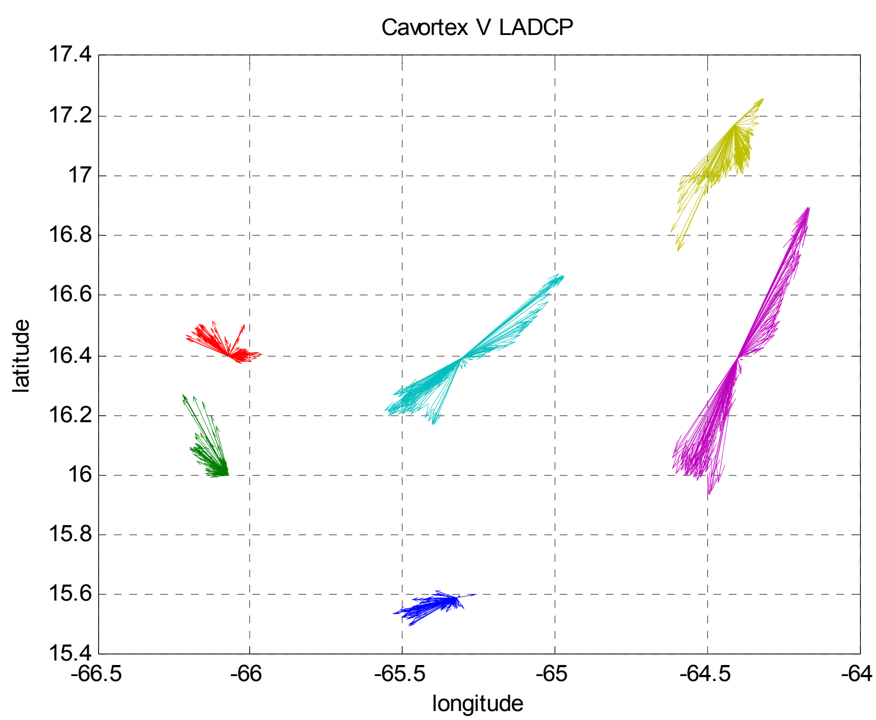

Figure 17. Current vectors at the six stations occupied during the third leg.

D. CaVortEx 6 Oceanographic Cruise

Cruise CaVortEx 6 was recently (Aug – Sept 2006) undertaken with the purpose of further characterizing cyclonic and anti-cyclonic eddies in the central Caribbean. Specific goals were:

- To quantify " eddy pumping" effects by cyclonic eddies in the Caribbean, and,

- To characterize fine scale eddy structure by means of a towed undulating instrument package

- To characterize eddy entrainnment of the Orinoco River plume and upwelling waters off the north coast of South America

A cruise track overlaid on an image of Sea Surface Height Anomaly (SSHA) is presented below.

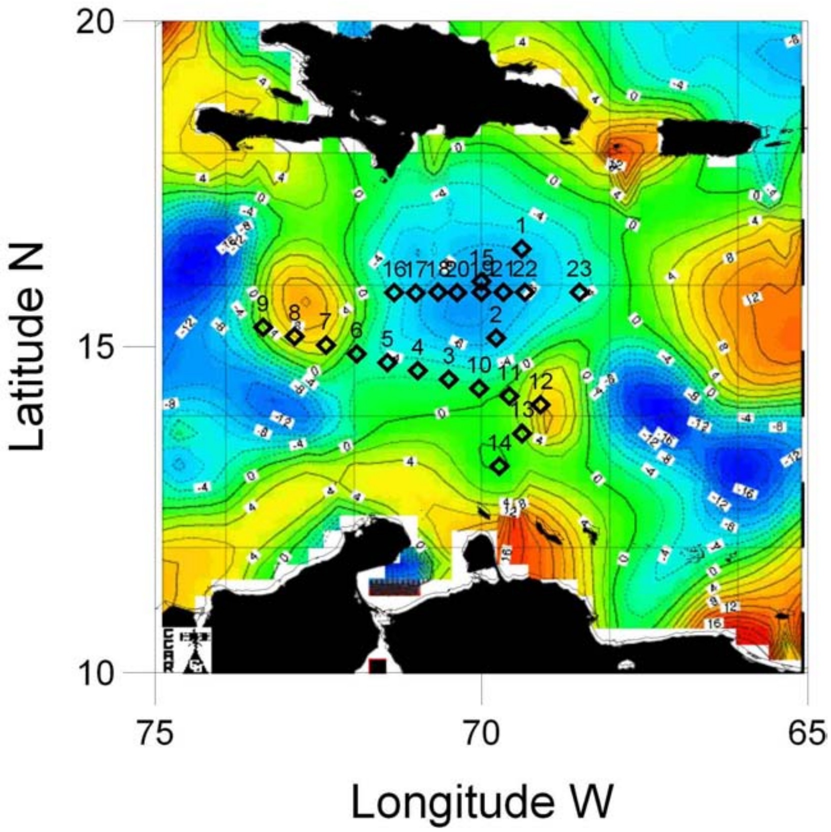

Figure 18. CaVortEx 6 cruise track overlaid on an image of SSHA for Sept 4 2006.

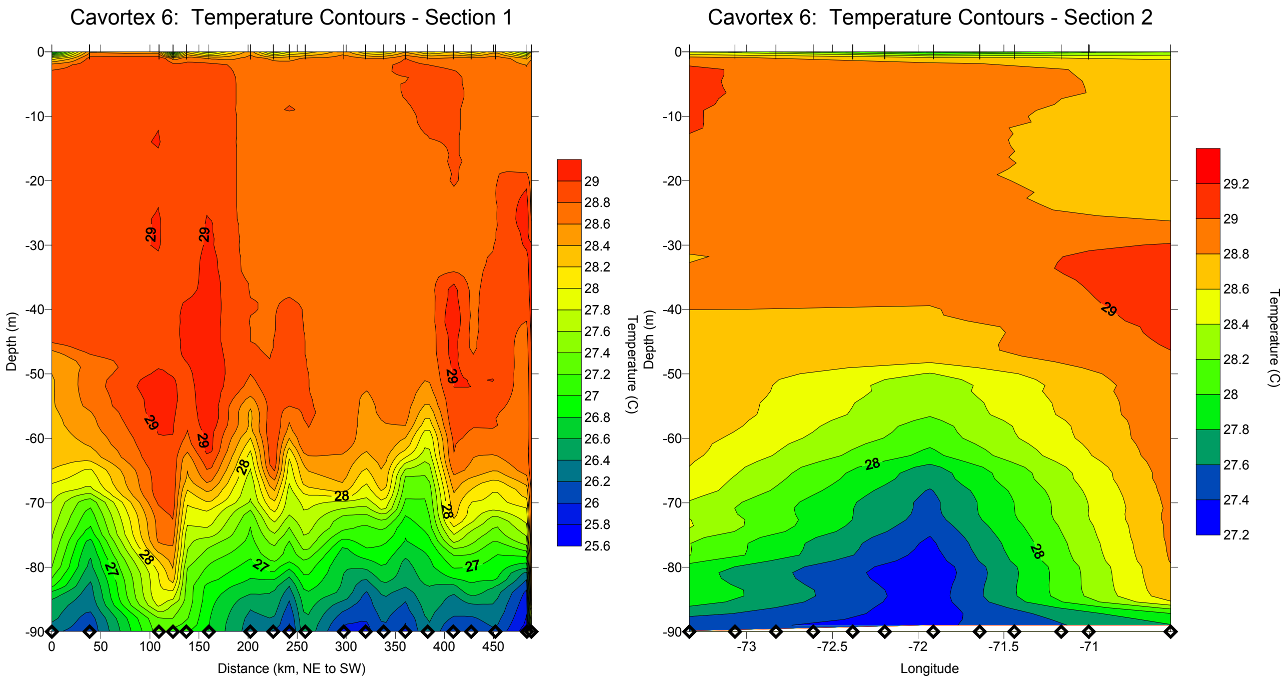

Figure 19. Isotherm contours in upper 90 meters across sections 1 and 2 show doming by eddy features

High Resolution, Undulating Underwater Data Collection System results

High Resolution, Undulating Underwater Data Collection System transects were sampled across a cyclonic and anti-cyclonic eddies as well as zones devoid of mesoscale features identifiable by satellite altimetry. Typically,   the oscillation range and frequency followed for these runs results in 75 oscillations per 30 nautical miles at depth ranging from. 15 to 90m. Upper water column structure observed trough this approach documented excursions of the upper thermocline, halocline and subsurface chlorophyll maxima expected to occur in eddy regions. Moreover, data indicates the widespread occurrence (both within and outside of eddies) of vertical excursions in the 5 to 20 meter range with apparent wavelengths ranging from 4 to 15 km. Often these coincided with localized enhancement of chlorophyll and or decreases in beam attenuation coefficient (c 670). Further analysis will provide more information regarding the prevalent amplitude of these outstanding features.

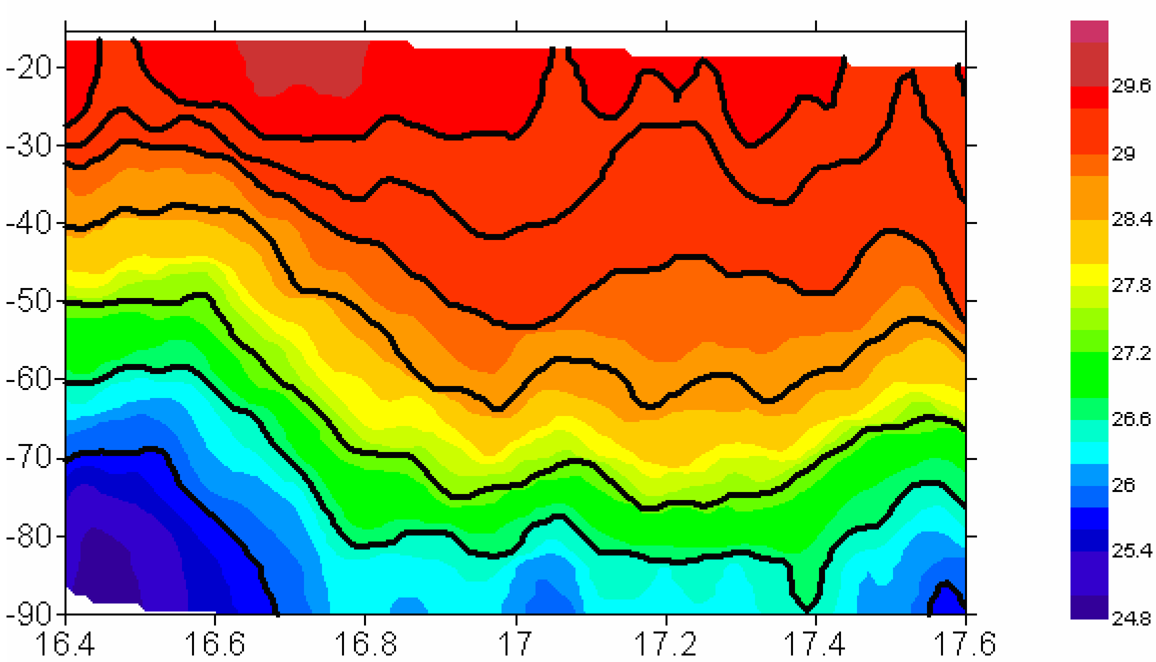

Figure 20. Isotherm contours of upper 90 meters across section devoid of eddy structures

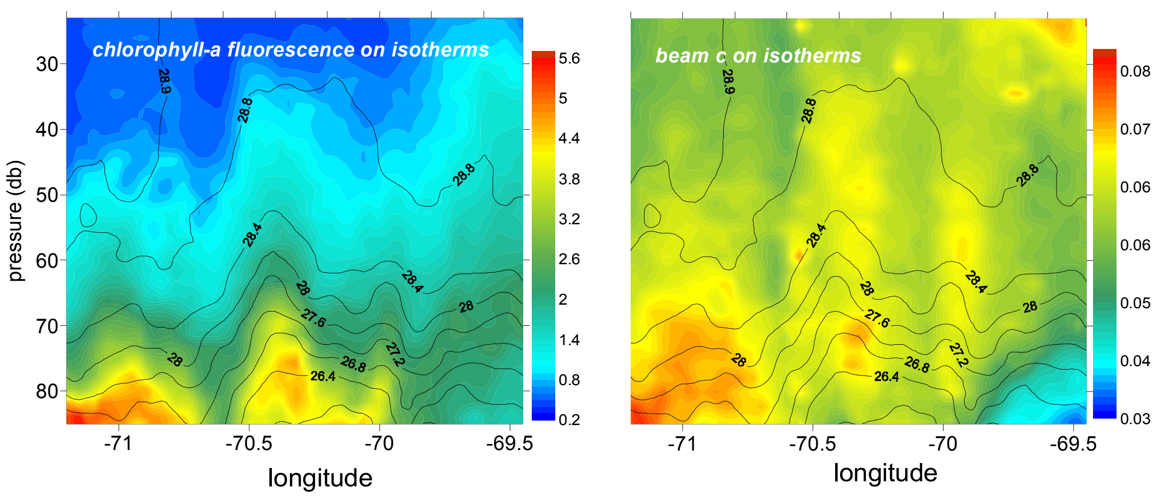

Figure 21. Isotherm contours of upper 90 m overlaid on chlorophyll-a fluorescence color map indicates the widespread occurrence (both within and outside of eddies) of vertical excursions in the 5 to 20 meter range with apparent wavelengths ranging from 4 to 15 km. Often these coincided with localized enhancement of chlorophyll and or decreases in beam attenuation coefficient (c 670).

Eddy pumping results

A fine-scale nutrient sampling pattern at selected isopycnals spanning the euphotic zone was undertaken across the cyclonic eddy depicted in Figure 18 in order to characterize nutrient drawdown attributable to eddy pumping. Preliminary results indicate measurable, but low, nutrient drawdown within the eddy core. Post cruise analysis of eddy displacement across the region using Sea Surface Height Aanomaly (SSHA) will allow computation of effective nutrient drawdown.

IMPACT/APPLICATIONS

Thermocline staircasing has been linked to enhanced diffusivity and modification of subsurface thermohaline structure. Although its potential impact on acoustic and optical character remains to be more profoundly investigated, identification of mechanisms driving its development will provide the necessary framework for developing such studies.

Validation of satellite borne estimates of optical properties of Eastern Caribbean waters and identification of eddies as a factor driving deviations from climatological means provides an adequate framework for combining ocean color imagery with altimetry for the prediction of the in situ optical character of surface waters in the region.

PUBLICATIONS

Morell J. M., and Corredor, J. E., Merryfield, W., “Thermohaline staircases in a Caribbean eddy and mechanisms for staircase formation”, Deep-Sea Research II 53 (2006) 128–139.

Morell J. M., López ,J.M, Méndez, M. and Corredor, J. E., “Optical Signatures of Meso-scale features in the Eastern Caribbean Basin”JGR (2006 in review).

López ,J.M, Canals M.F., Capella, J., Morell J. M., and Corredor, J. E. “Structure Of Caribbean Eddies” OS16D-24 Poster, Ocean Sciences Meeting, Hawaii (2006)