Characterization of Caribbean Meso-Scale Eddies

Jose M. Lopez
Department of Marine Sciences, P.O. Box 9013, Mayaguez, Puerto Rico 00681-9013
phone: (787) 832-4040 x 5229 fax: (787) 834-8025 email: jlopez@uprm.edu

Jorge E. Corredor
Department of Marine Sciences, P.O. Box 908,Lajas, Puerto Rico 00667-908
phone: (787) 899-2049 fax: (787) 899-3838 email: j_corredor@ cima.uprm.edu

Julio M. Morell
Department of Marine Sciences, P.O. Box 908, Lajas, Puerto Rico 00667-908
phone: (787) 899-2049 fax: (787) 899-3838 email: j_morell@cima.uprm.edu

Jorge E. Capella
Department of Marine Sciences, P.O. Box 908, Lajas, Puerto Rico 00667-908
phone: (787) 899-2049 fax: (787) 899-3838 email: jcapella@caribe.net

Fernando Gilbes
Department of Geology, P.O. Box 9001, Mayaguez, Puerto Rico 00681-9001
phone: (787) 834-7620 fax: (787) 265-6340 email: gilbes@cacique.uprm.edu

Grant Number: N000140310904

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). An expected outcome 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

- To determine the distribution of physical, chemical, biological and optical variables across frontal and eddy boundaries in the Eastern Caribbean Sea
- To develop sub regional derivation of empirical relationships between horizontal and vertical physical/chemical gradients and remotely sensed ocean properties
- Verification of inherent optical properties predicted by NRL's Automated Software System
- Verification of the eddy structure and trajectory predictions by the $1/16^{o}$ operational global NRL Layered Ocean Model
- Correlations of phytoplankton pigment composition and size class distribution to inherent optical properties

APPROACH

We are implementing a series of research cruises to carry out observations of the optical and physical structure and upper water column biogeochemistry of eddies. Eddy distribution and displacement will be 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 (F.Gilbes). During research cruises we will obtain continuous flow surface records of T, S and Chl-a (J. Corredor), vertical sections of these variables plus apparent optical properties using the Nν-shuttle undulating towed body (J. Lopez). Discrete vertical profiles (J. Morell, J. Corredor) of physical (T, S), chemical (DO, nutrients, CDOM), biological and inherent (a, b, c) and apparent (R, R_{RS}, T, K_z) optical properties (F. Gilbes) will be obtained. Selected samples will be subjected to 3-D spectrofluorometry and scanning spectrophotometry for CDOM characterization (J. Corredor, J. Morell). Current structure across fronts and eddies will be characterized by means of ship-lowered ADCP current profiler (J. Capella). These studies will also include assessment of rates of biomass accumulation, primary production and photosynthetic efficiency (J. Lopez).

WORK COMPLETED

Cruise CaVortEx II aboard R/V CHAPMAN, June 10 -18 2004, was undertaken in order to characterize an eddy pair traversing the eastern Caribbean Sea. This was the second in a series of cruises devoted to the characterization of meso-scale eddies in Caribbean waters. Navy models predicted a strong cyclonic and weak-to-moderate /anti-cylconic eddy pair traversing the eastern Caribbean in the US EEZ. The cruise track (Fig. 1) was programmed to provide a section across both eddies. Post-cruise evaluation of cruise data and model results indicate that the cyclonic eddy strengthened during the time for the cruise but the projected small anti-cyclonic eddy south of St. Croix did not develop significantly. Operations included deployment of Nu-shuttle towed underwater undulating vehicle(continuous nighttime throughout cruise), XBT casts and oceanographic stations with cast of Optical rosette (inherent optical properties), PRR 600 (Profiling Reflectance Radiometer-6 SeaWiFS bands), LISST-100 Laser Induced Sediment Scattering and Transmissometry, Lowered ADCP (acoustic doppler current profiler and CTD/rosette cast to 1000 m.

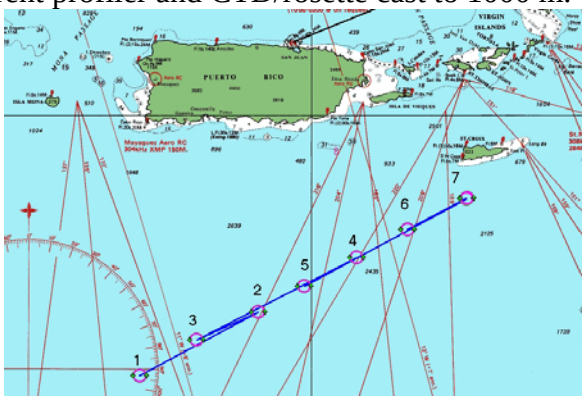

Figure 1. CaVortEx II station positions and cruise track

RESULTS

NLOM SSH projections predicted persistence of a strong cyclonic feature south of Puerto Rico and the advection of a small anti-cyclonic eddy towards the south east of St. Croix during the time of the cruise. A transect running southwest to northeast was projected to intersect both of these expected

features. NLOM and NOAA CoastWatch SSH analysis confirmed the persistence of the cyclonic feature but indicate that there was poor development of the expected anti-cyclonic feature (Fig. 2). MODIS ocean color imagery for the week of June 25 to July 2 shows the intrusion of a moderately high chlorophyll filament along the NE edge of the cyclonic feature. The Naval Research Laboratory, Intra-Americas Sea Ocean Nowcast/Forecast System model product for sea surface salinity (http://www7320.nrlssc.navy.mil/IASNFS_WWW/IASNFS_arc.html) for 06/24/2004 shows intrusion of low salinity water (<35.3) at a similar location. (Fig. 3). These analysis indicate that CaVortEx II successfully sampled the cyclonic feature.

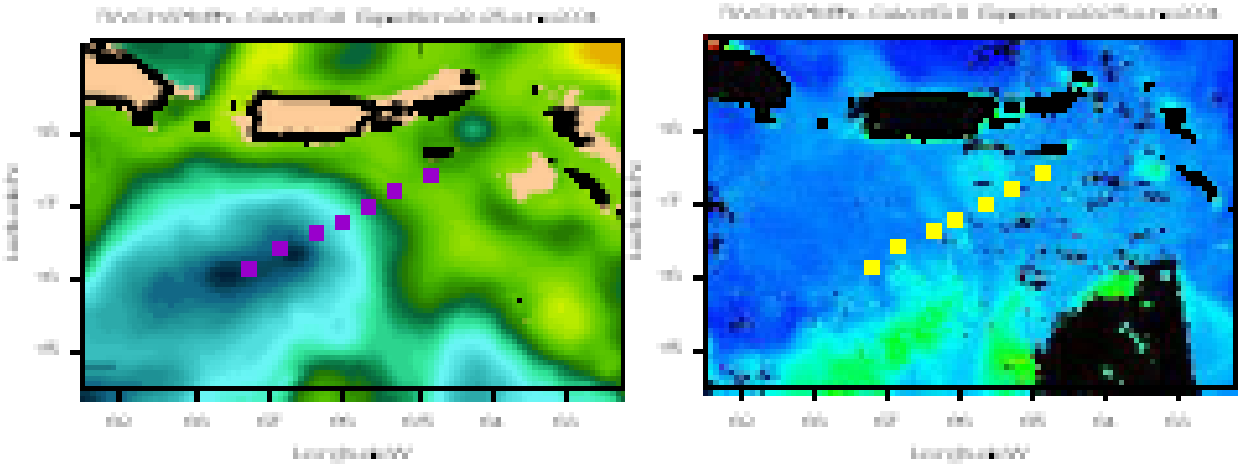

Figure 2. Cruise track overlaid on:(left) NLOM 1/32o sea surface height analysis for 06/25/04 and (right) composite MODIS Chlorophyll for 06/25/04 – 07/05/04

Profiles of temperature, salinity, density, chlorophyll a and turbidity obtained with the CTD package (Figure 3) provide a view of subsurface physical and biogeochemical structure during the cruise.

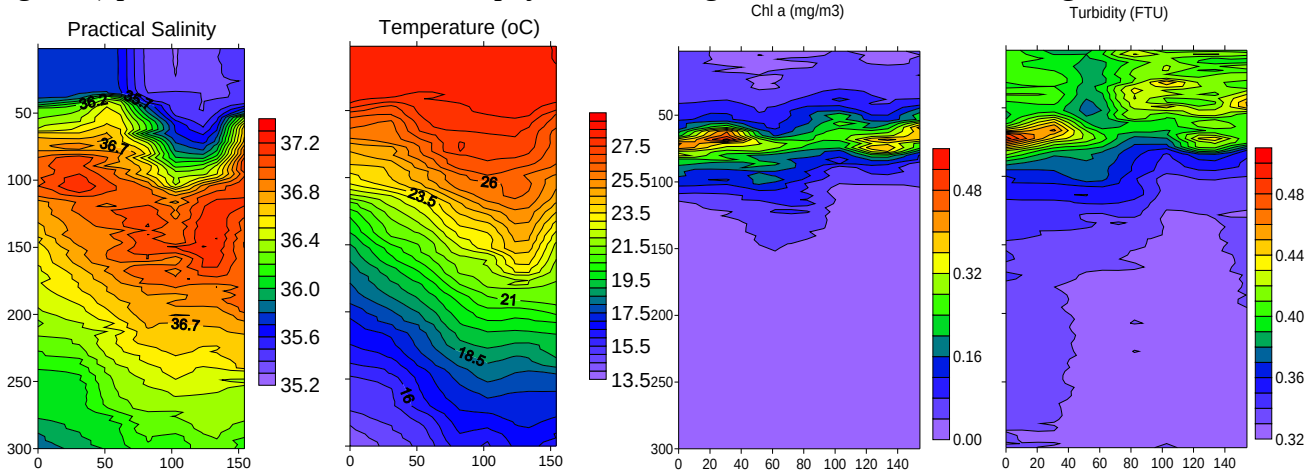

Figure 3, (panels from left to right) isohalines, isotherms, equal chl-a and equal turbidity contour plots to 300m along 150nm trnasect

The density section shows isopycnal shoaling towards the SW throughout the transect. At intermediate depths (300-700m) transient isopycnal lift occurs at about 115 nautical miles (nm) along transect. Upper water column structure is more complex with additional isopycnal elevations at 90 and 150 nm along transect. Dynamic height anomalies and corresponding geostrophic velocities are consistent with the occurrence of a strong cyclone in the SW portion of the transect, a weak anti-cyclone in the NE. Near surface practical salinity ranged from 35.29 in the SW to 35.79 at 103 nm along transect.

Near-surface salinity domes upward in the SW and downward in the NE. A sharp surface salinity discontinuity is apparent at ca. 60 nm along transect with the low salinity lens, probably an extension of the Amazon River plume, to the NE confined to the upper 50 m. The salinity discontinuity is accompanied by a sharp transient reduction of near-surface chlorophyll and turbidity. Chl a domes upward in the SW and downward in the NE conforming to behavior expected from a cylonic/anti-cylonic eddy pair. Turbidity dropped significantly below ca. 100m throughout the transect indicating the existing of optically dense surface water masses to this depth separated by the discontinuity of low turbidity water marking the boundary between cyclonic and anti-cylonic flow. Sections obtained with the Nu-Shuttle show a wealth of detail in the upper water column structure (Fig. 4) confirming cyclonic doming in the SE and the low salinity intrusion at ca. 66.75 W.

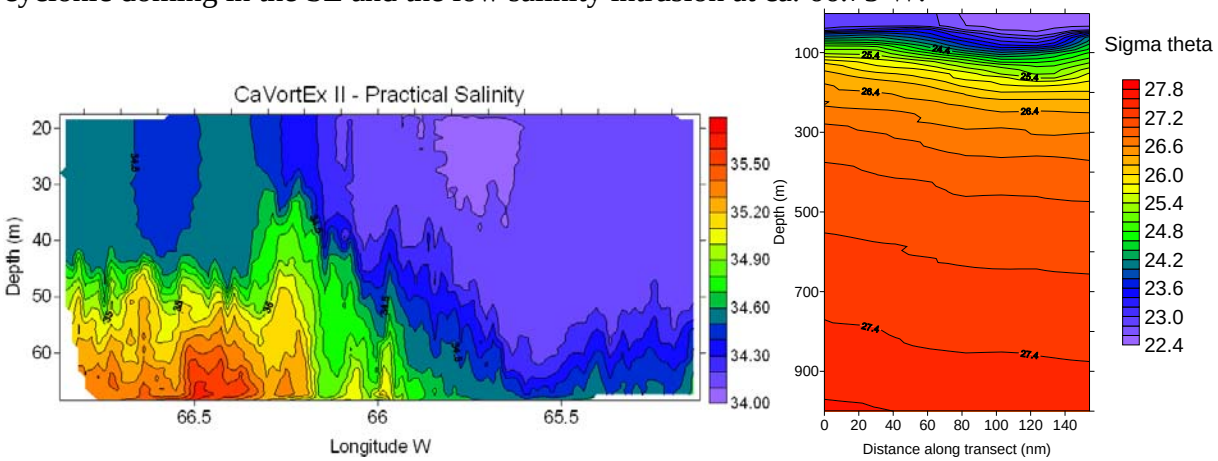

Figure 4. (left panel) Nu-Shuttle salinity section; (right panel) CTD sections isopygnals to 1km along 150 nm transect

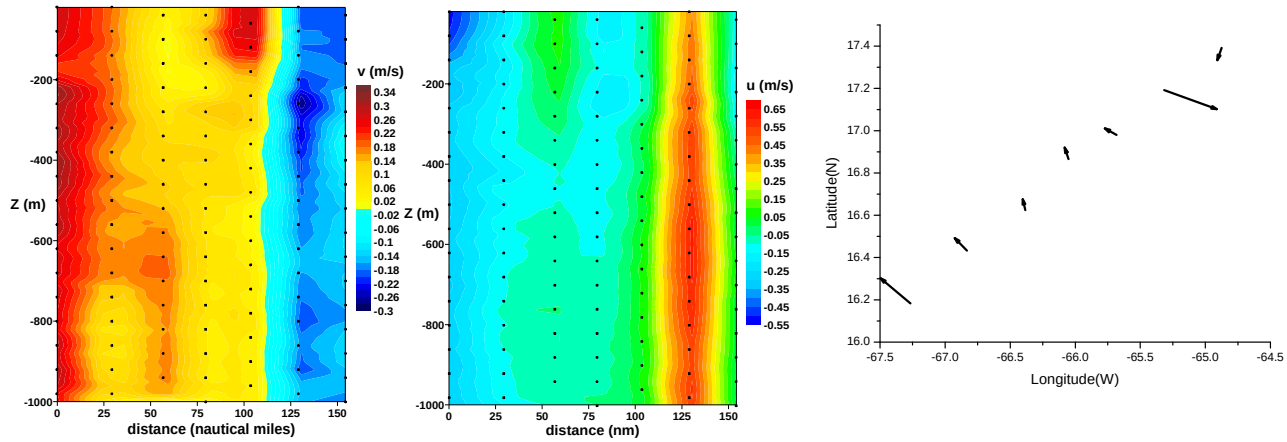

Figure 5. Contour plot of (left panel) magnitude of the meridional component of current velocity. Shades of yellow/red denote a positive (to the north) component, shades of blue represent a negative (to the south) component; (middle panel) magnitude of the zonal component of current velocity and (right panel) Mean current magnitude and direction for all 7 stations during Cavortex II for the upper 1000 meters. The tail of the arrow represents the geographic position of the station. The largest arrow represents a speed of 60.6 cm/s, the smallest a speed of 13.4 cm/s.

Cross sections showing contours of equal value of the Inherent Optical Properties (IOP) coefficients of absorption, beam attenuation and scattering across the cruise transect of 260 km and down to 160 m of depth reveal close correlation of the distribution of the IOP with physical and biological features that are apparent from Figures 3-5. The IOP complement are explained by the hydrographic data.

We show representative plots for the IOP at 412 nm which follow a similar distribution as for other visible wavebands that are also available in our data base from ac-9 and Hydroscat-6 (Fig 6).

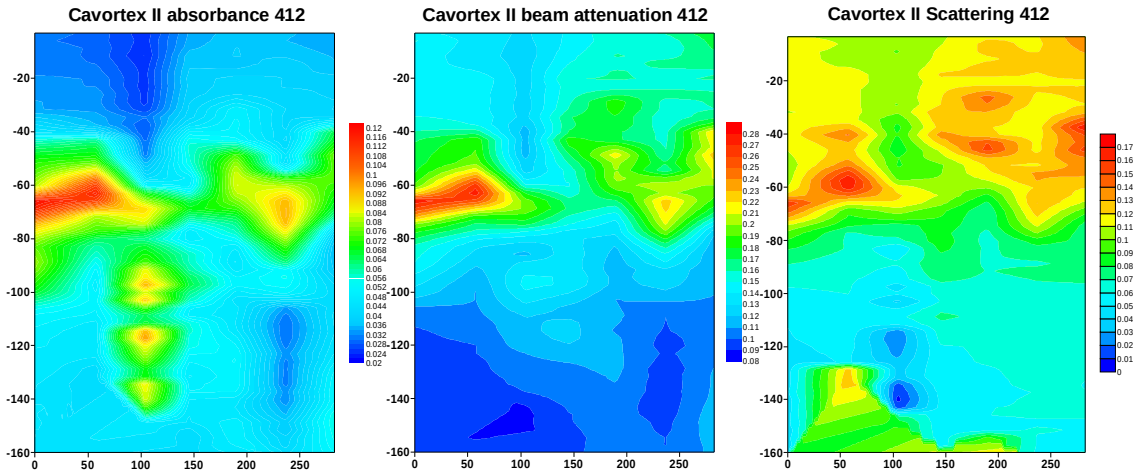

Figure 6. Contour plots for, coefficient of absorption (left), beam attenuation and scattering down to 160m depth and 260km transect

IMPACT/APPLICATIONS

Paired cyclonic/anti-cyclonic eddies travel across the Eastern Caribbean sea from east to west and can conveniently be reached from Puerto Rico for oceanographic study of their physical, biological and optical structure and dynamics. Cyclonic eddies have been invoked as powerful drivers of biogeochemical fluxes in the tropical ocean as well as significant vectors for inter-hemispheric transport. Such roles have aroused interest from scientists in a wide range of fields. The capability to remotely characterize these features as well as to predict their properties and dynamics should allow for more precise modelling of the role these mesoscale features play in the global ocean. In a regional context, the occurrence of these mesoscale events further contributes to the optical and biogeochemical complexity of Eastern Caribbean waters where other mesoscale phenomena, the discharge of two of the world's major rivers and coastal upwelling, sustain pronounced physical chemical and biological gradients. Knowledge of the interaction of these features with eddies will allow a more complete understanding of the optical heterogeneity of the region and its forecasting.

RELATED PROJECTS

A UPRM/NASA-sponsored research program, entitled Tropical Center for Earth and Space Studies, includes an oceanography component focused on identifying factors limiting biological carbon fixation in the Western Tropical Atlantic and Caribbean Sea. This program has funded the acquisition of instrumentation applicable to the effort here described and provided ocean color satellite imagery and partial ship time funding for the CaVortEx I cruise.

PUBLICATIONS

Corredor JE, J. M.Morell, JM.Lopez, JE Capella And R. A.Armstrong "Cyclonic Eddy Entrains Orinoco River Plume in Eastern Caribbean" Eos,Vol. 85, No. 20, 18 May 2004.

Characterization of Caribbean Meso-Scale Eddies

José M. López
Department of Marine Sciences, University of Puerto Rico,
P.O. Box 9013, Mayaguez, Puerto Rico 00681-9013
phone: (787) 832-4040 x 5229 fax: (787) 834-8025 email: jlopez@uprm.edu

Jorge E. Corredor
Department of Marine Sciences, University of Puerto Rico,
P.O. Box 908, Lajas, Puerto Rico 00667-908
phone: (787) 899-2049 fax: (787) 899-3838 email: j_corredor@ cima.uprm.edu

Julio M. Morell
Department of Marine Sciences, University of Puerto Rico,
P.O. Box 908, Lajas, Puerto Rico 00667-908
phone: (787) 899-2049 fax: (787) 899-3838 email: j_morell@cima.uprm.edu

Jorge E. Capella
Department of Marine Sciences, University of Puerto Rico,
P.O. Box 908, Lajas, Puerto Rico 00667-908
phone: (787) 899-2049 fax: (787) 899-3838 email: jcapella@caribe.net

Fernando Gilbes
Department of Geology, University of Puerto Rico,
P.O. Box 9001, Mayaguez, Puerto Rico 00681-9001
phone: (787) 834-7620 fax: (787) 265-6340 email: gilbes@cacique.uprm.edu

Grant Number: N000140310904

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.
- 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.

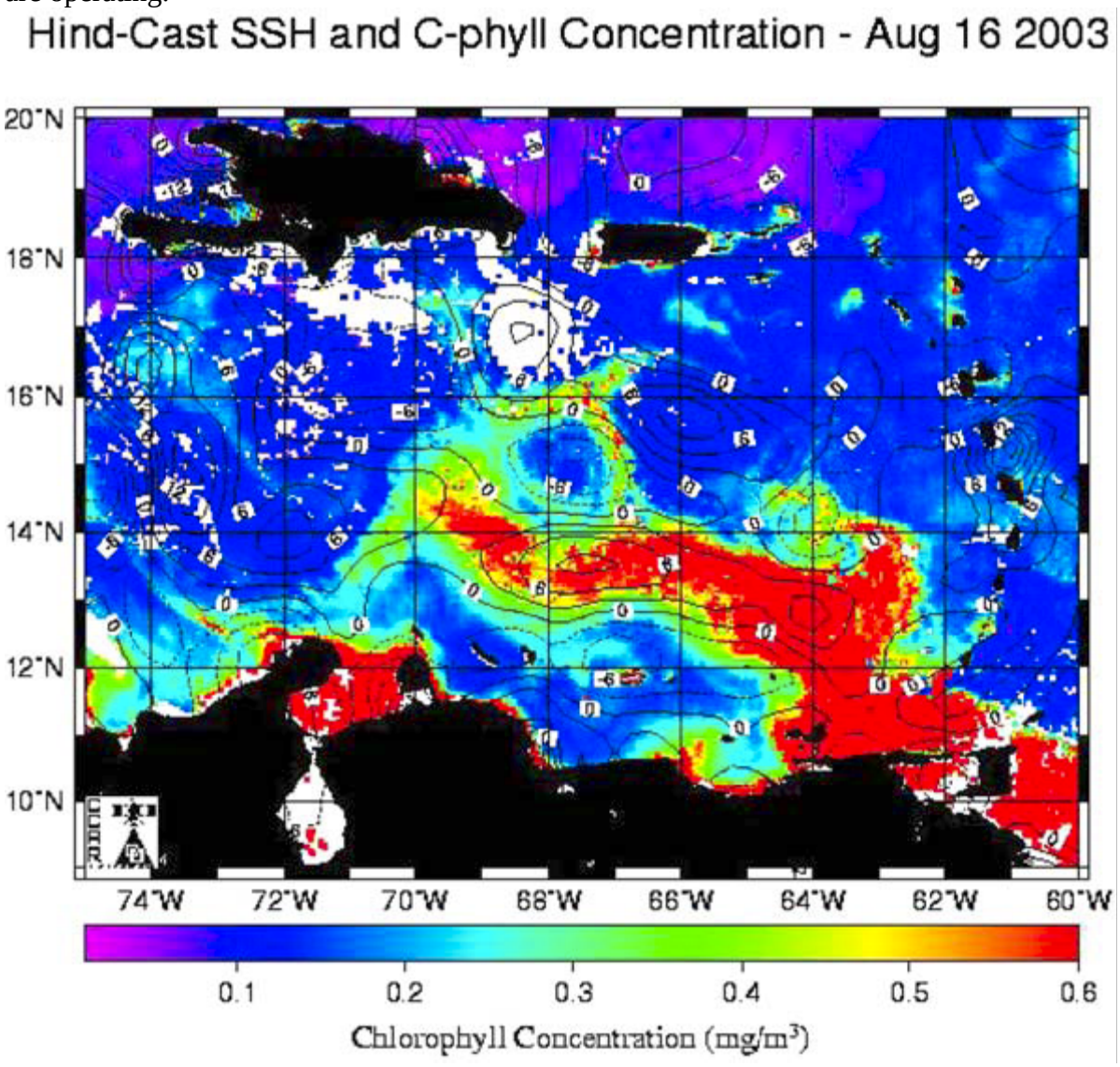

Fig. 1. Chlorophyll concentration (colors) and sea-surface height anomalies (contours labeled in cm) in the eastern Caribbean on August 16, 2003. The center of the cyclonic eddy traversed during CaVortEx I lies in the near 15N, 67’500W in a region of negative sea-surface height anomaly. The Orinoco River 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.)

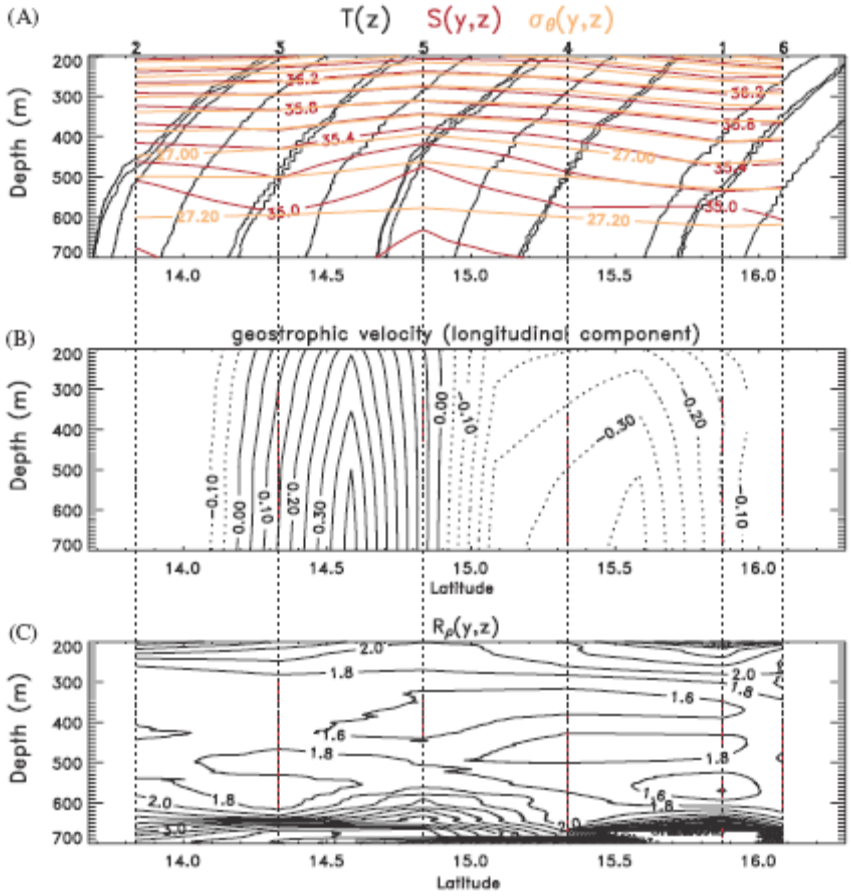

Fig. 2. (A) T versus depth from CTD measurements (thick black curves) and XBT casts (thin black curves). Traces are plotted on an arbitrary scale, and are offset from each other by distances proportional to the latitudinal spacing between stations. Red contours denote isohalines and orange curves isopycnals, 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.

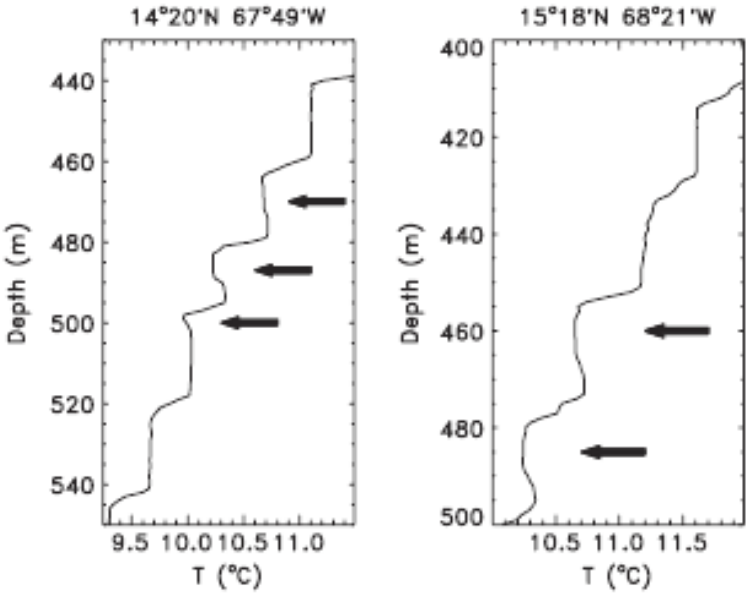

Fig. 3 Temperature as a function of depth at two of the CaVortEx I CTD stations, showing intrusion-like inversions within some steps (arrows).

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.

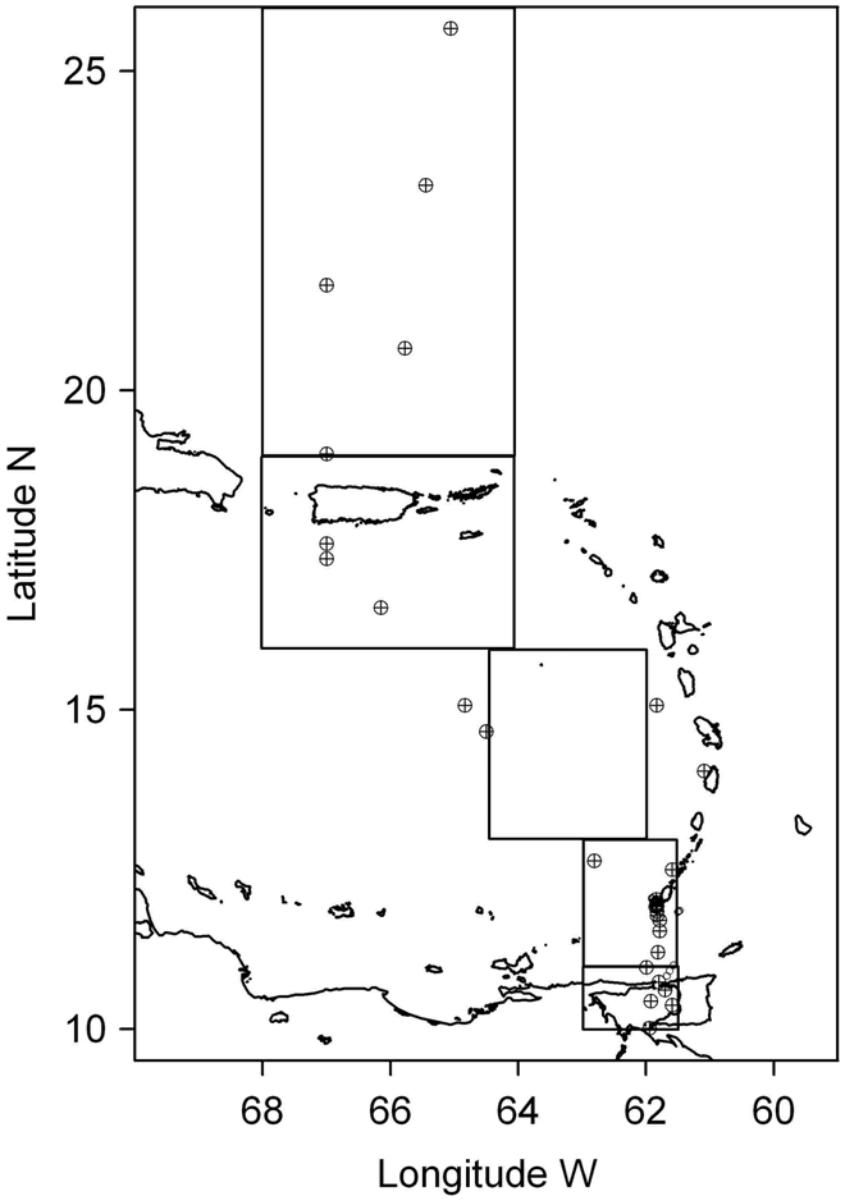

Figure 4. Map of the ECB depicting oceanographic sampling stations. Boxes indicate sub-regions selected for analysis of satellite remote sensing products.

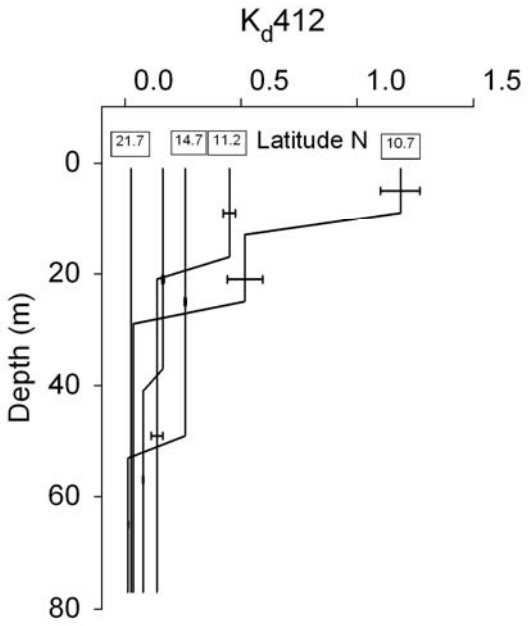

Figure 5. Representative vertical profiles for Kd412 across the latitudinal gradient. Kd412 values in the river plume at low latitudes are high but values at depth below the plume approach the near-surface values of oceanic waters at higher latitudes.

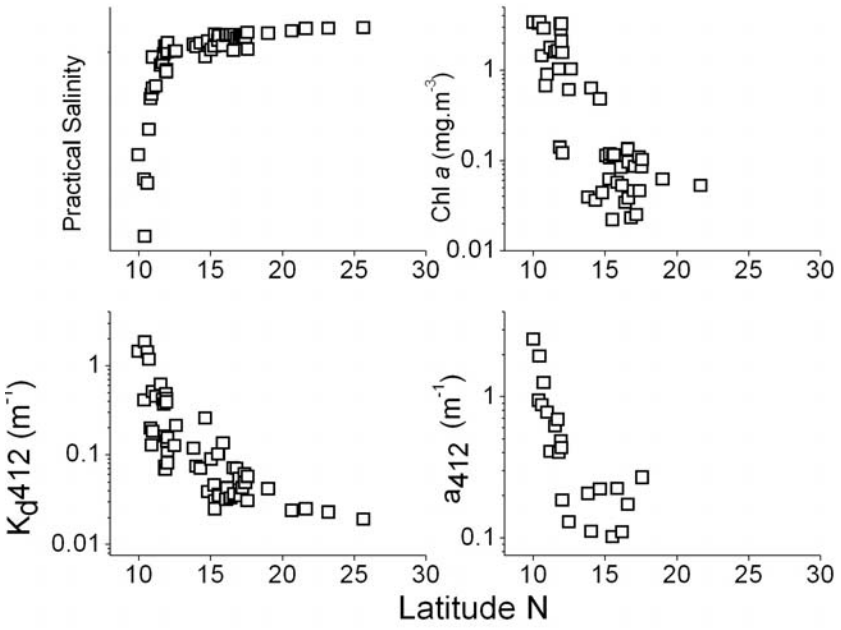

Figure 6. Plots of logarithmic transforms of near-surface practical salinity, Chl a, K_d412 and a $_{412}$ vs. latitude. The relationship between K_d412 and latitude can be described by an exponential decay function ($r^2 = 0.62$; n = 60).

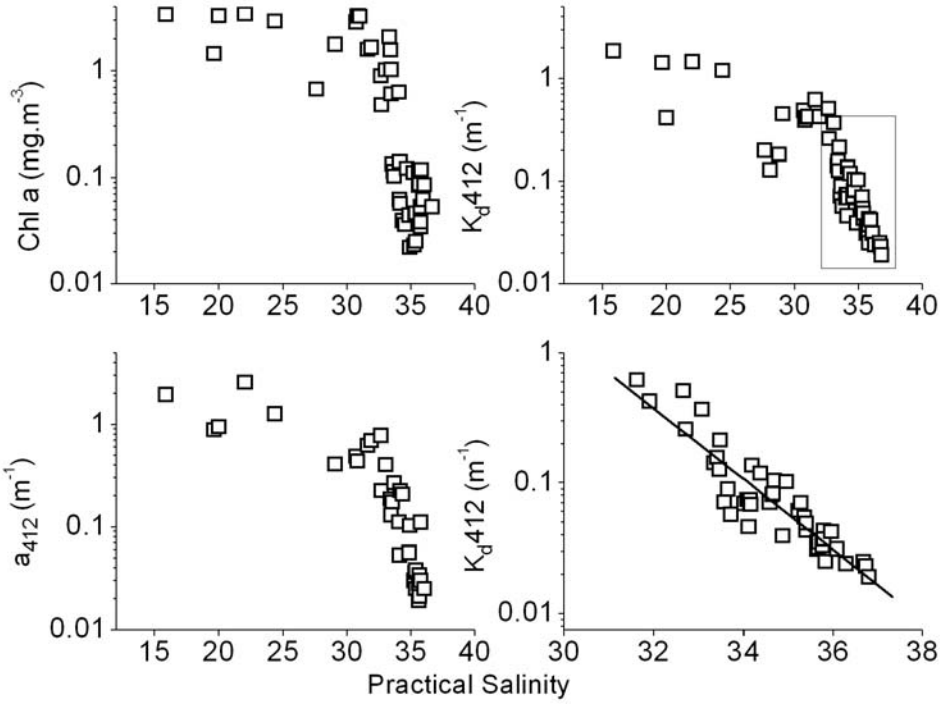

Figure 7. Plots of logarithmic transforms of near-surface Chl a, Kd412 and a 412 vs. practical salinity. A subset of the data in the top right panel, denoted by the box, consists of values above practical salinity 30, is plotted in the lower right panel. The relationship between salinity and Kd412 in 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.

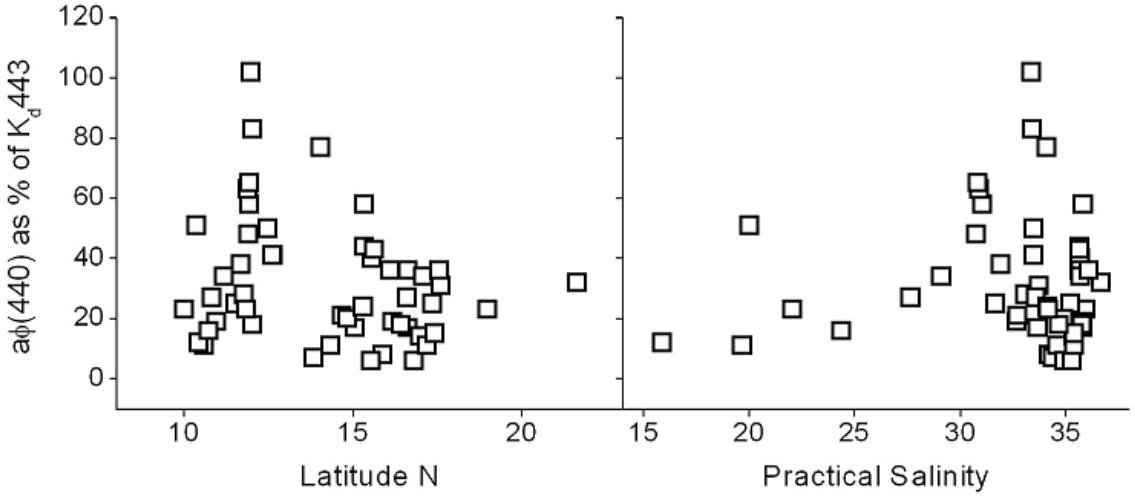

Figure 8. Plots of phytoplankton absorption at 440 nm, computed from our in situ Chl a values and the expression of Bricaud et al. (2004), vs. latitude (left) and salinity (right).

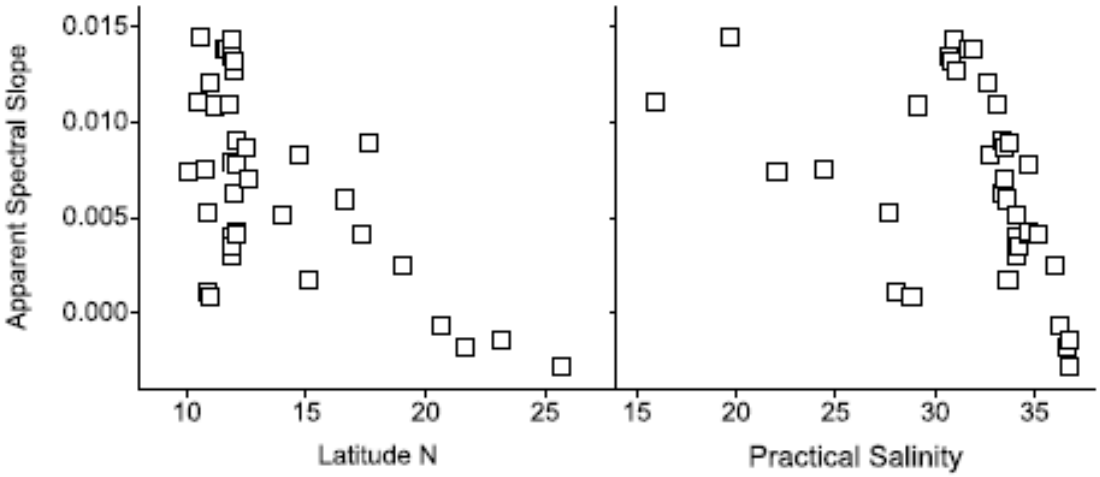

Figure 9. Plot of apparent spectral slope (SA) vs. latitude (left) and salinity (right). The linear decay of SA with salinity reflects CDOM photodegradation.

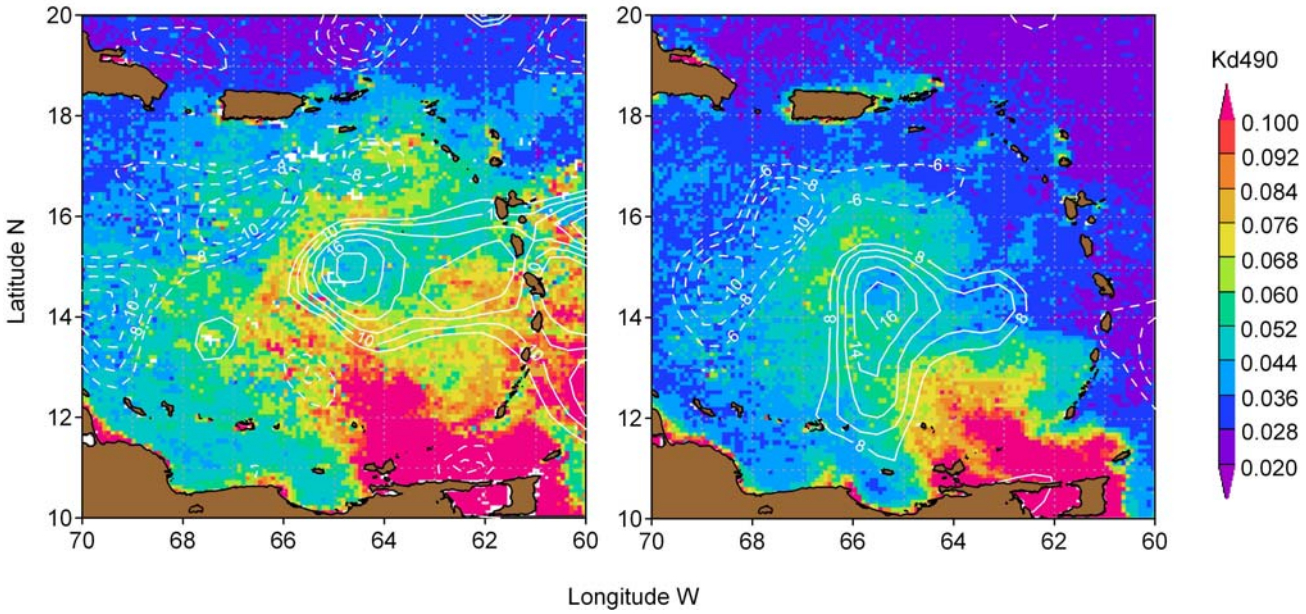

Figure 10. Satellite derived images of Kd490 (m-1) distribution in the ECB with a Sea Surface Height Anomaly (SSHA)
(cm) overlay depicting eddy-plume interactions. Left: June 2002. Right: December 2003.
River plume trajectory is constrained by eddy size and rotational direction.

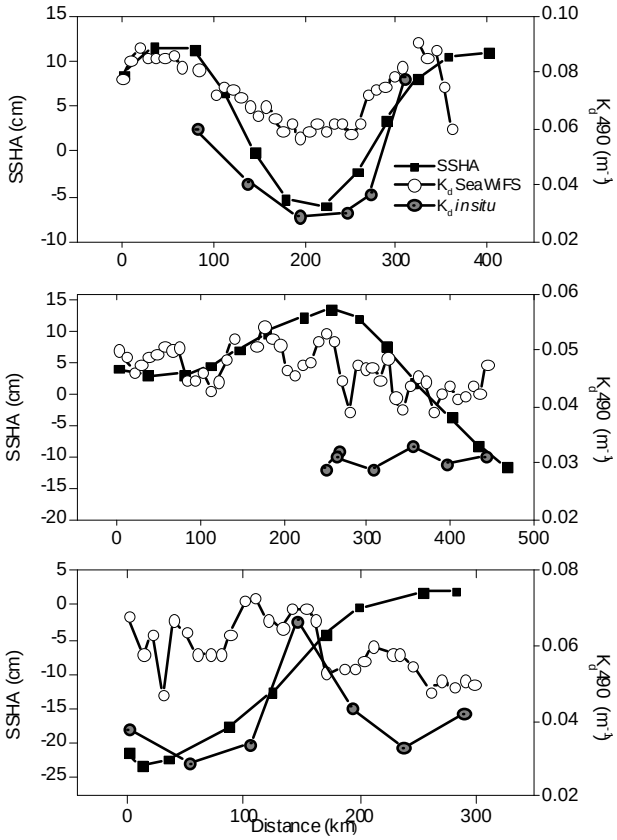

Figure 11. Plots of SSHA from AVISO 7 day composites of multiple satellites (black), SeaWiFS K_d490 from level 3, 9 km resolution weekly composites (white) and in situ K_d490 (gray) across: (top) a cyclonic eddy in the ECB. SSHA 16 August 2003, SeaWiFS K_d490 13- 20 August 2003 both along 67^o W longitude, in situ data 16 – 19 August 2003 along 67.8^o W.; (middle) an eddy pair in the ECB: in situ data along a transect from 16^o 10’ N 67^o 15’ W to 17^o 25’ N 64^o 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^o 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.

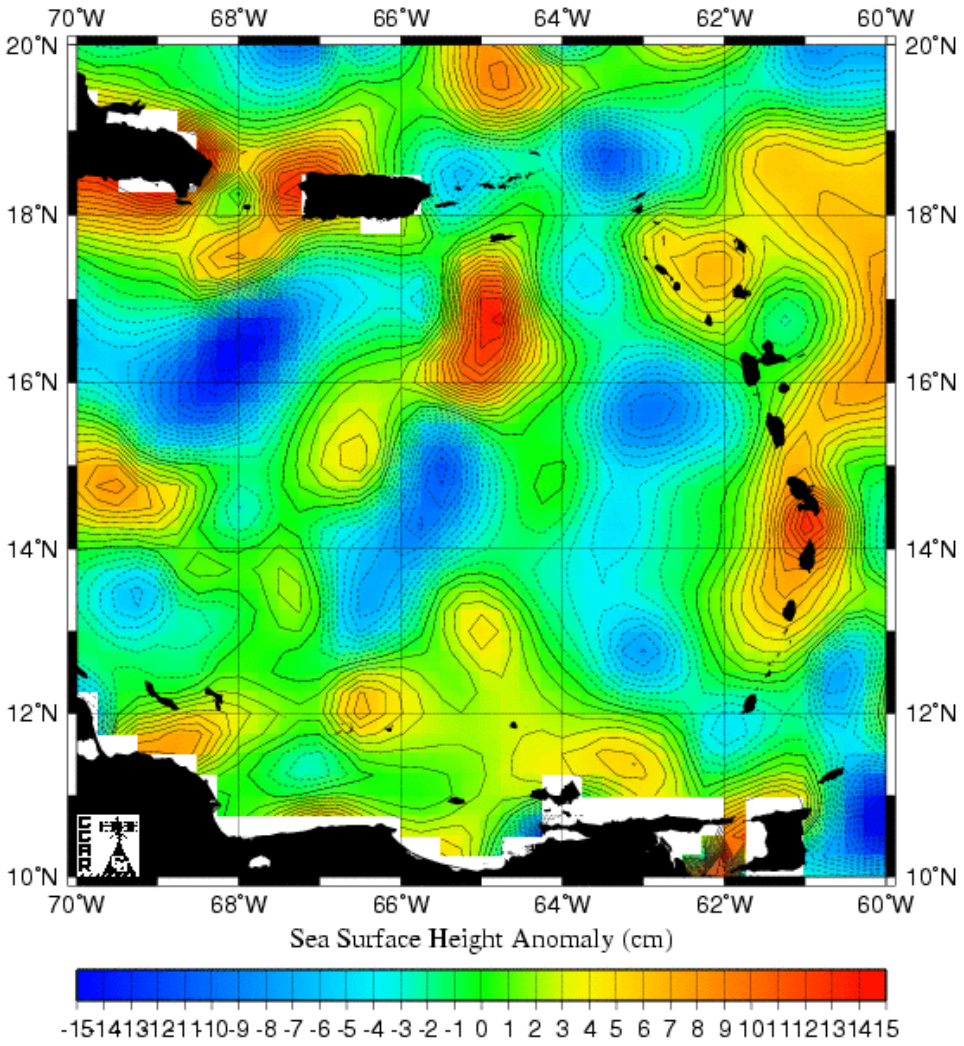

Figure 12. Sea surface height anomaly satellite image during November 24, 2005.

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).

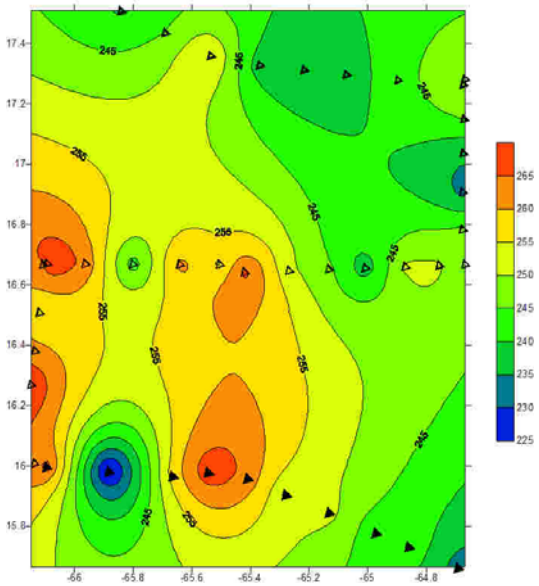

Fig 12. Cvtx 5: XBT 18°C Topography

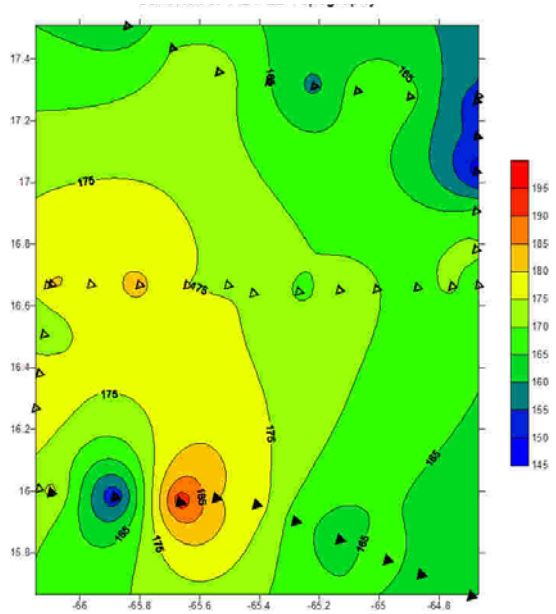

Fig 13. Cvtx 5: XBT 22°C Topography

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).

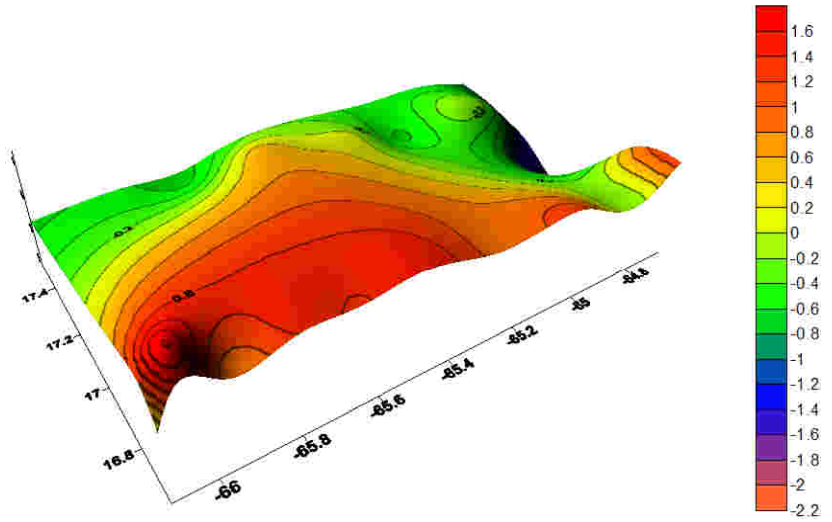

Figure 14. Cvtx temperature anomalies at 90 m.

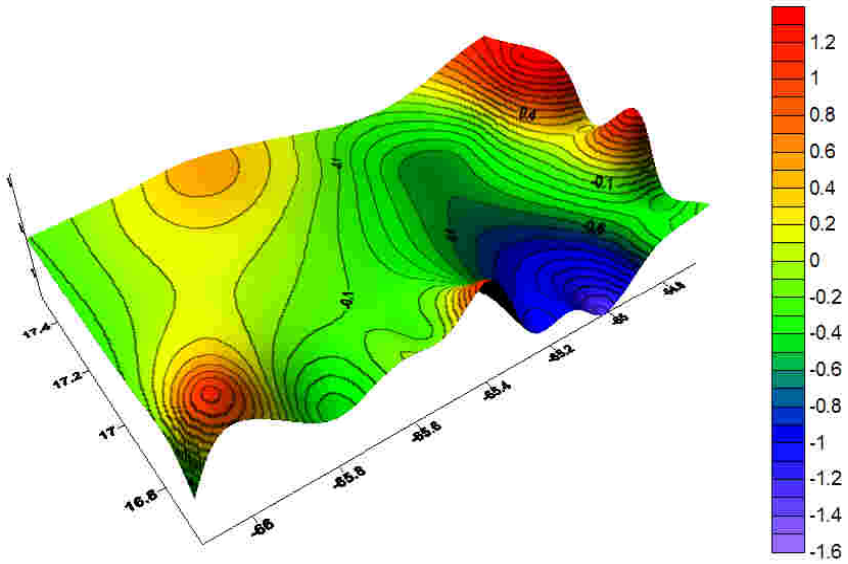

Figure 15. Cvtx temperature anomalies at 450 m.

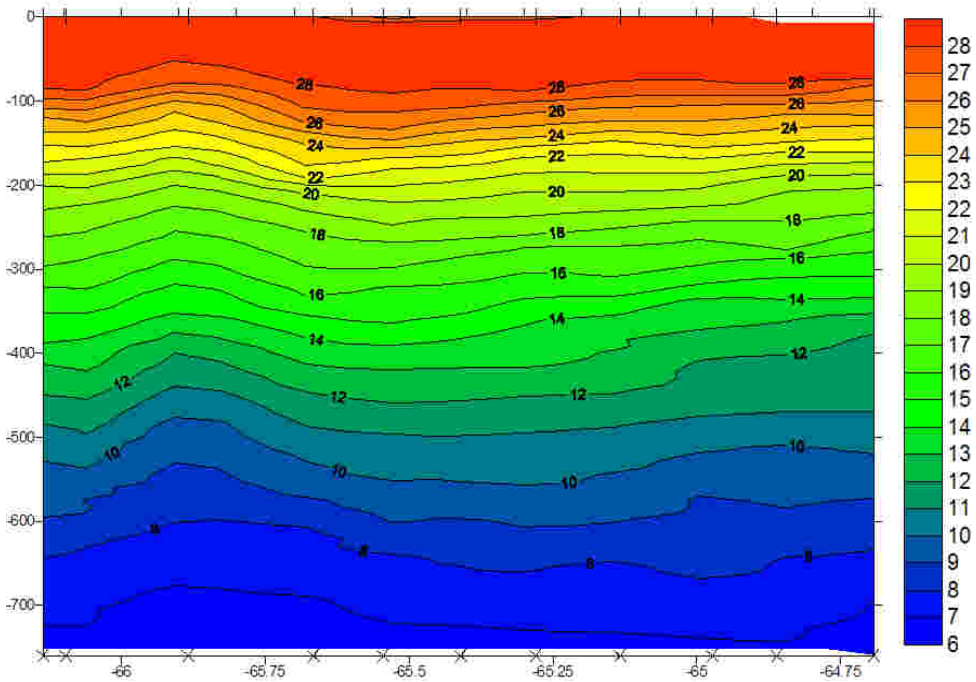

Figure 16. Temperature isoclines contour along a meridian transect at 16.6°N.

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.

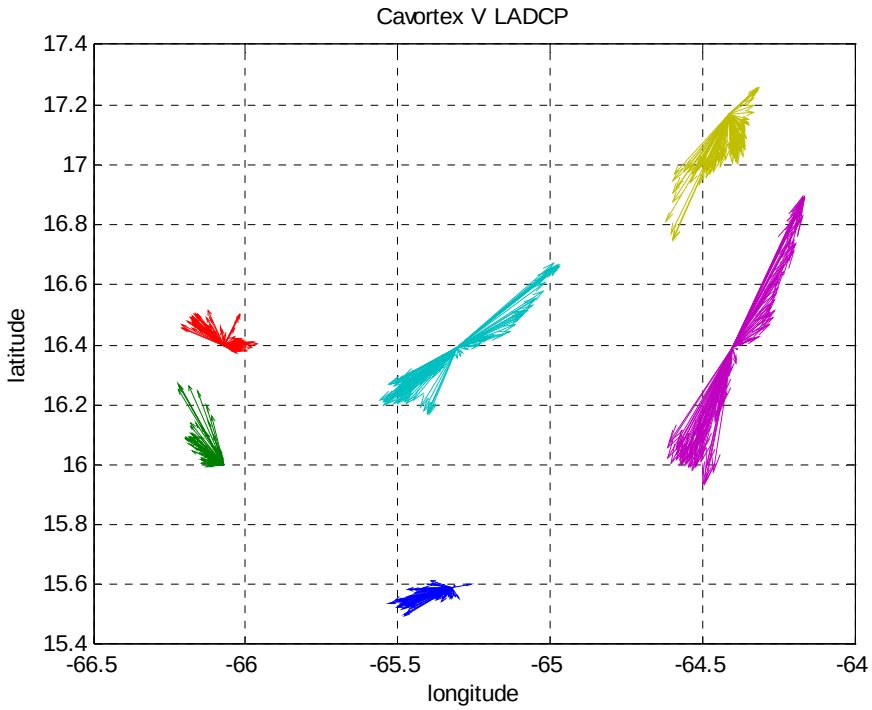

Figure 17. Current vectors at the six stations occupied during the third leg.

B. 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.

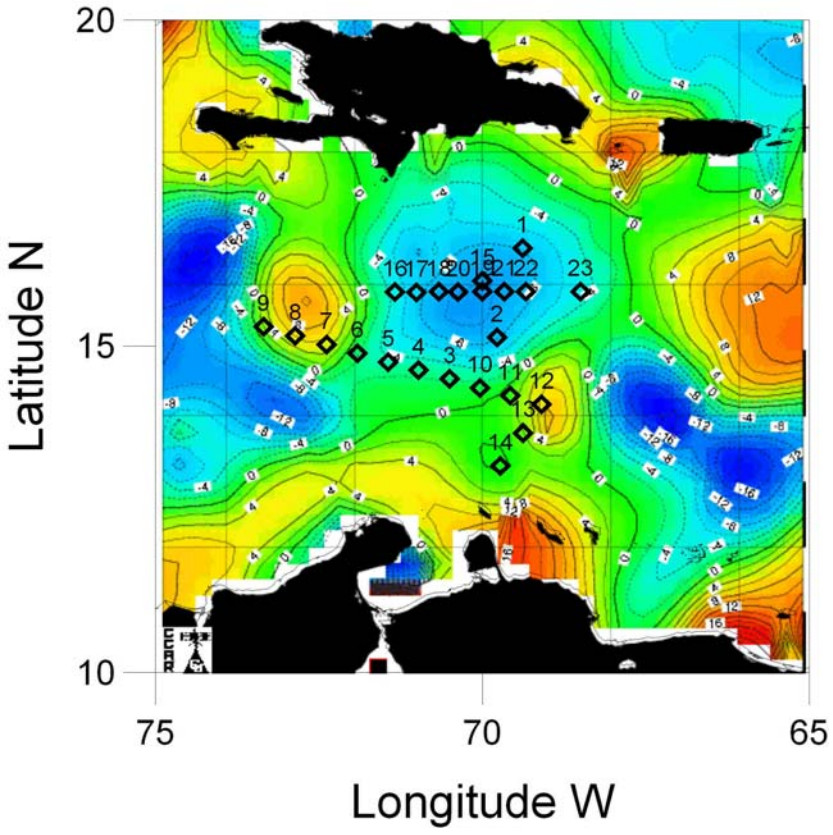

Figure 18. CaVortEx 6 cruise track overlaid on an image of SSHA for Sept 4 2006.

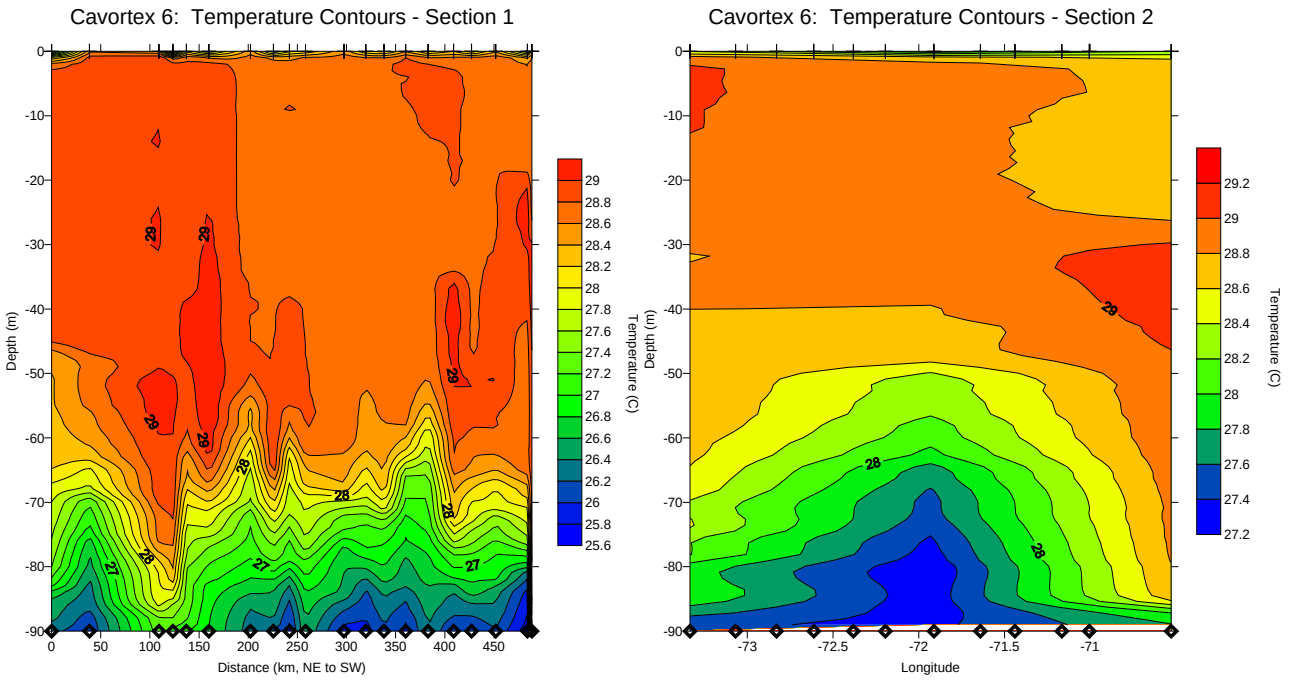

Figure 19. Isotherm contours in upper 90 meters across sections 1 and 2 show doming by eddy features

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.

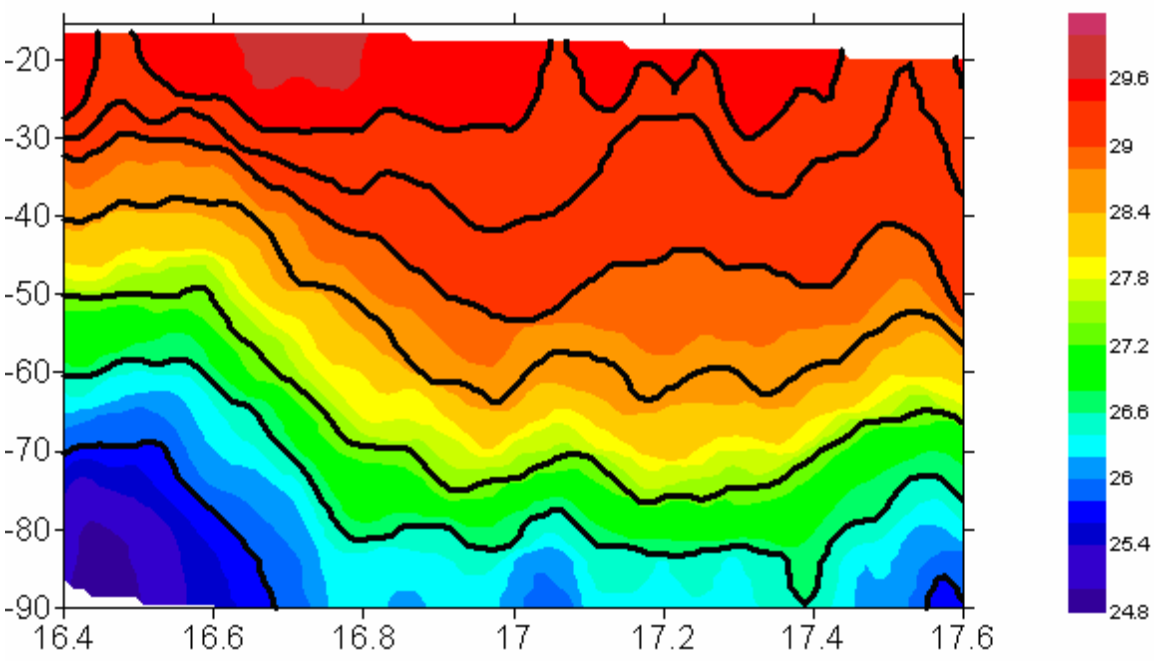

Figure 20. Isotherm contours of upper 90 meters across section devoid of eddy structures

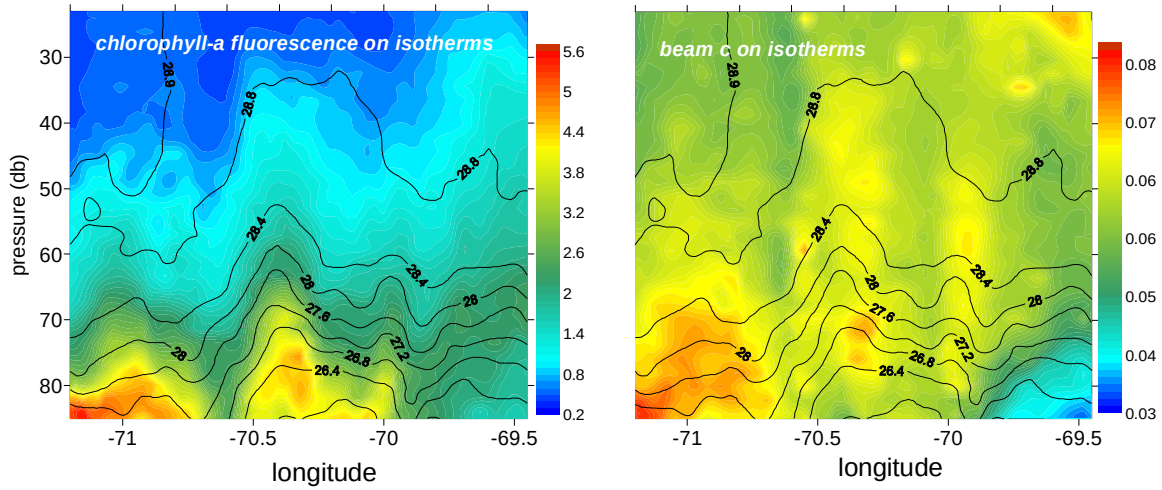

Figure 21. Isotherm contours of upper 90 m overlaid on chlorophyll-a fluorescence color map indicates the widespread occurrence (both within and outside of eddies) of vertical excursions in the 5 to 20 meter range with apparent wavelengths ranging from 4 to 15 km. Often these coincided with localized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

Corredor, J.E., J.M. Morell, J.M. López, J.E. Capella, and R.A. Armstrong, Cyclonic Eddy Entrains Orinoco River Plume in Eastern Caribbean, EOS Trans. Amer. Geophys. U., 85 (20), 197; 201-202, 2004

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)

Characterization of Caribbean Meso-Scale Eddies

José M. López
Department of Marine Sciences, University of Puerto Rico,
P.O. Box 9013, Mayaguez, Puerto Rico 00681-9013
phone: (787) 832-4040 x 5229 fax: (787) 834-8025 email: jlopez@uprm.edu

Jorge E. Corredor
Department of Marine Sciences, University of Puerto Rico,
P.O. Box 908, Lajas, Puerto Rico 00667-908
phone: (787) 899-2049 fax: (787) 899-3838 email: j_corredor@ cima.uprm.edu

Julio M. Morell
Department of Marine Sciences, University of Puerto Rico,
P.O. Box 908, Lajas, Puerto Rico 00667-908
phone: (787) 899-2049 fax: (787) 899-3838 email: j_morell@cima.uprm.edu

Jorge E. Capella
Department of Marine Sciences, University of Puerto Rico,
P.O. Box 908, Lajas, Puerto Rico 00667-908
phone: (787) 899-2049 fax: (787) 899-3838 email: jcapella@caribe.net

Fernando Gilbes
Department of Geology, University of Puerto Rico,
P.O. Box 9001, Mayaguez, Puerto Rico 00681-9001
phone: (787) 834-7620 fax: (787) 265-6340 email: gilbes@cacique.uprm.edu

Grant Number: N000140310904

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

- Characterization of the horizontal and vertical physical/biogeochemical gradients and their interaction with optical properties across fronts, eddy structures and massive river plume discharges in the Eastern Caribbean Sea.

- Explore empirical relationships between remotely sensed ocean color and sea surface height and 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

In FY 07, we conducted data analysis and synthesis of CaVortEx 6 Oceanographic Cruise which was completed in Sep 2006 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. Experiments 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. CaVortEx 6 Oceanographic Cruise

Cruise CaVortEx 6 was completed in 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

We present measurements of bio-optical and physical properties made in a mesoscale cyclonic eddy structure shown in maps of sea surface height anomaly (SSHA) in the Eastern Caribbean Sea region from space-based altimetry. Cruise tracks and sampling schemes (CTD and XBT casts) were designed to test model results which indicate that, under the influence of mesoscale eddies, primary frontal boundaries may undergo spatial modifications resulting in enhancement of vertical and horizontal flux and biogeochemical activity. Hydrographic and optics package casts as well as undulating underwater data collection systems were employed. Color maps of meridional sections of the inherent optical property, beam attenuation (beam c), and chlorophyll-a fluorescence overlaid on temperature and salinity data depict a rich pattern of associated vertical and horizontal features including fresh water entrainment, isopycnal doming, non chlorophyll-a particulate attenuation zones and cross pycnocline transport. We explore whether, for these cross sections, in-situ and remote ocean color data support the view that anti-cyclonic circulation results in increased biomass accumulation in contrast to cyclonic circulation. A cruise track overlaid on an image of Sea Surface Height Anomaly (SSHA) is presented below.

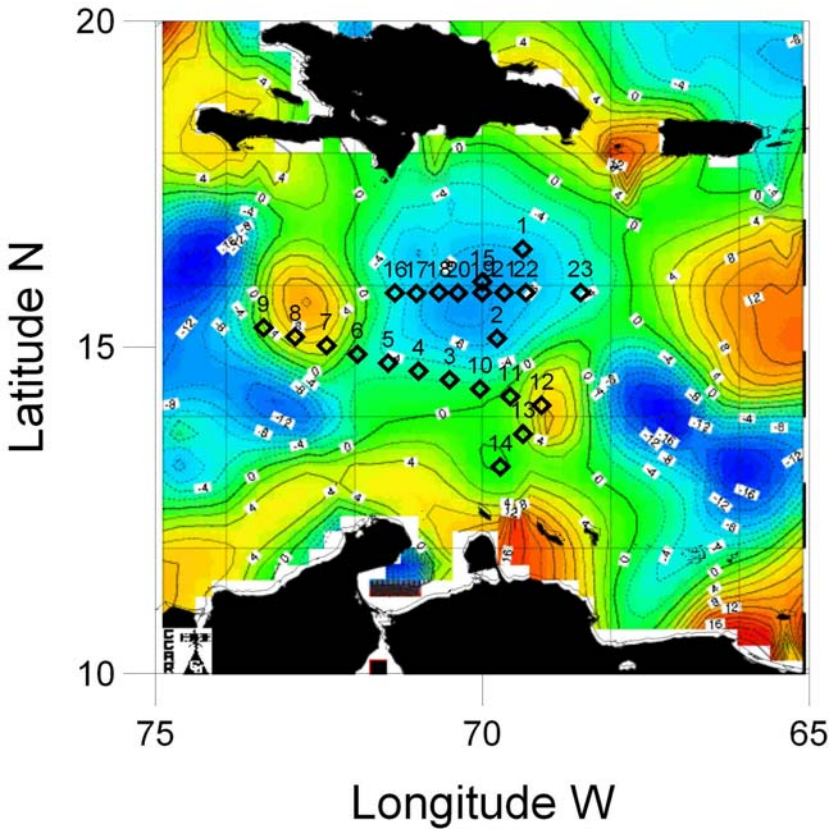

Figure 1. CaVortEx 6 cruise track map overlaid on an image of SSHA for Sept 4 2006 showing station sctions across cyclone and anticyclones.

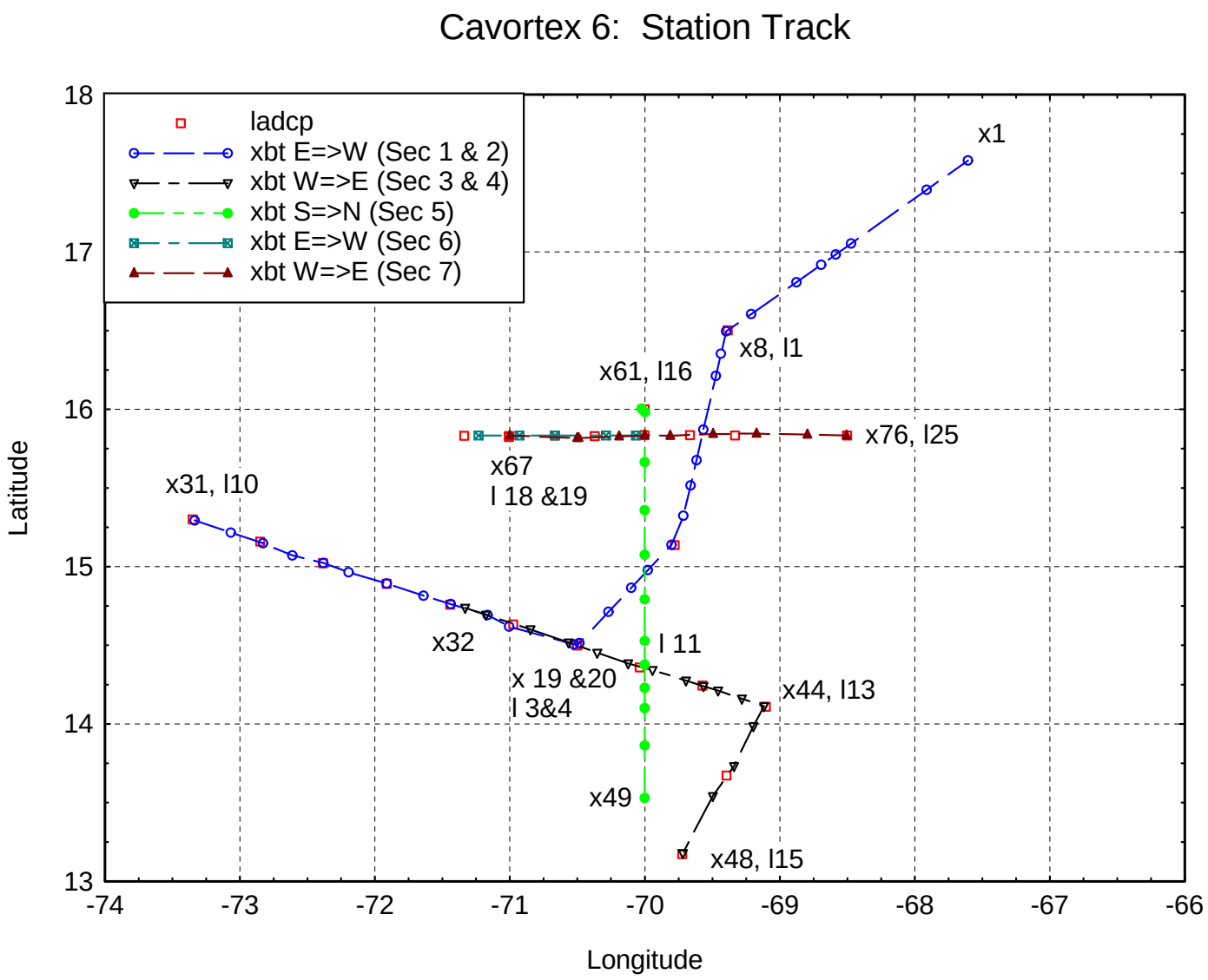

Figure 2. Summary plot of station positions (lat/lon) of Lowered Acoustic Doppler Current Profiler (LADCP) cast and Expendable Bathythermograph (XBT) East-West and North-South sections within a region bounded by 13 to 18 deg N and -74 to -67 E.

B. High Resolution, Undulating Underwater Data Collection System results

Figure 3. Shown on deck, real-time underway data collection system NuShuttle Undulating Underwater Vehicle carying CTD_Fluorometer, Fast Repetition Rate Fluorometer (FRRF) and Beam-c (660) transmisometer.

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).

C. Results for CTD and XBT Casts At 30 Km Horizontal Resolution

- Independent Temperature measurement profiles were made by CTD and XBT casts at nominally 30km horizontal intervals across a cyclonic eddy with nominal vertical resolution of less than 1 m. Meridional plots of eddy cross section from the interpolated data at this resolution show evidence of shallow doming of isotherms (Thermocline Eddy).

D. 1km Horizontal Resolution From Underwater Undulating Data System

- A much more complex physical and optical structure is revealed by the 1 km horizontal resolution (< I m vertical) data obtained with the Undulating Underwater Data Collection System across the same transect of the Cyclonic eddy.
- Upper water column structure observed through this approach documented intricate excursions (high rugosity of the surfaces) of the upper thermocline, halocline and subsurface chlorophyll maxima beyond that expected from “classical” eddy doming alone.
- The ratio of Beam c to Chlorophyll-a suggests surface accumulation of non-chlorophyll carbon in the cyclone core.
- 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 660).

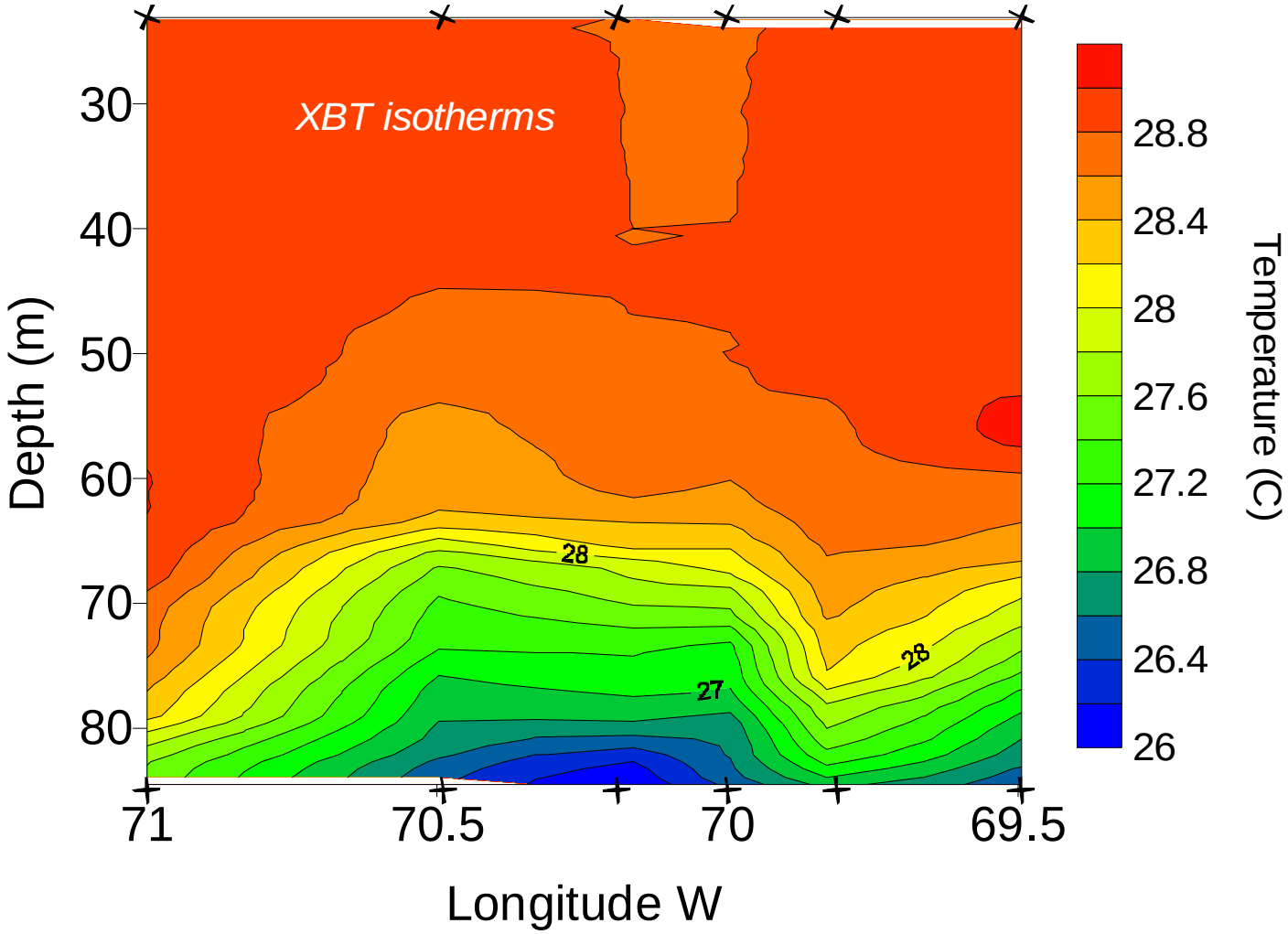

Figure 4. XBT-derived isotherms in upper 90m in cross section from 69.5 to 71.0 W reveals upward doming due to upwelling in cyclone. Black crosses at bottom and top of panel mark position of 6 xbt casts from which data is interpolated.

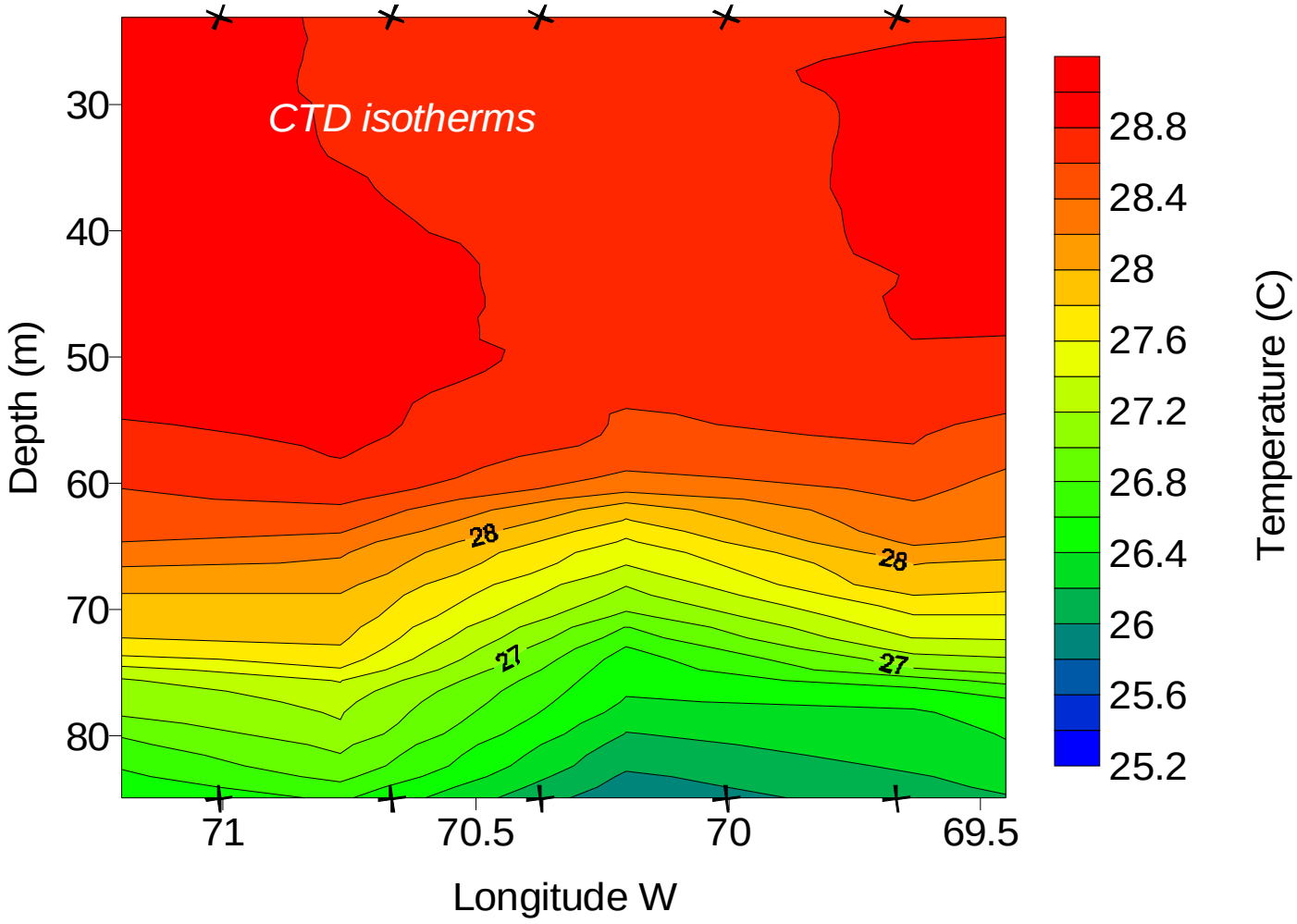

Figure 5. CTD-derived isotherms in upper 90m in cross section from 69.5 to 71.5 W suggests upward doming due to upwelling in cyclone. Resolution is poorer than XBT's. Black crosses at bottom and top of panel mark position of 5 CTD casts from which data is interpolated.

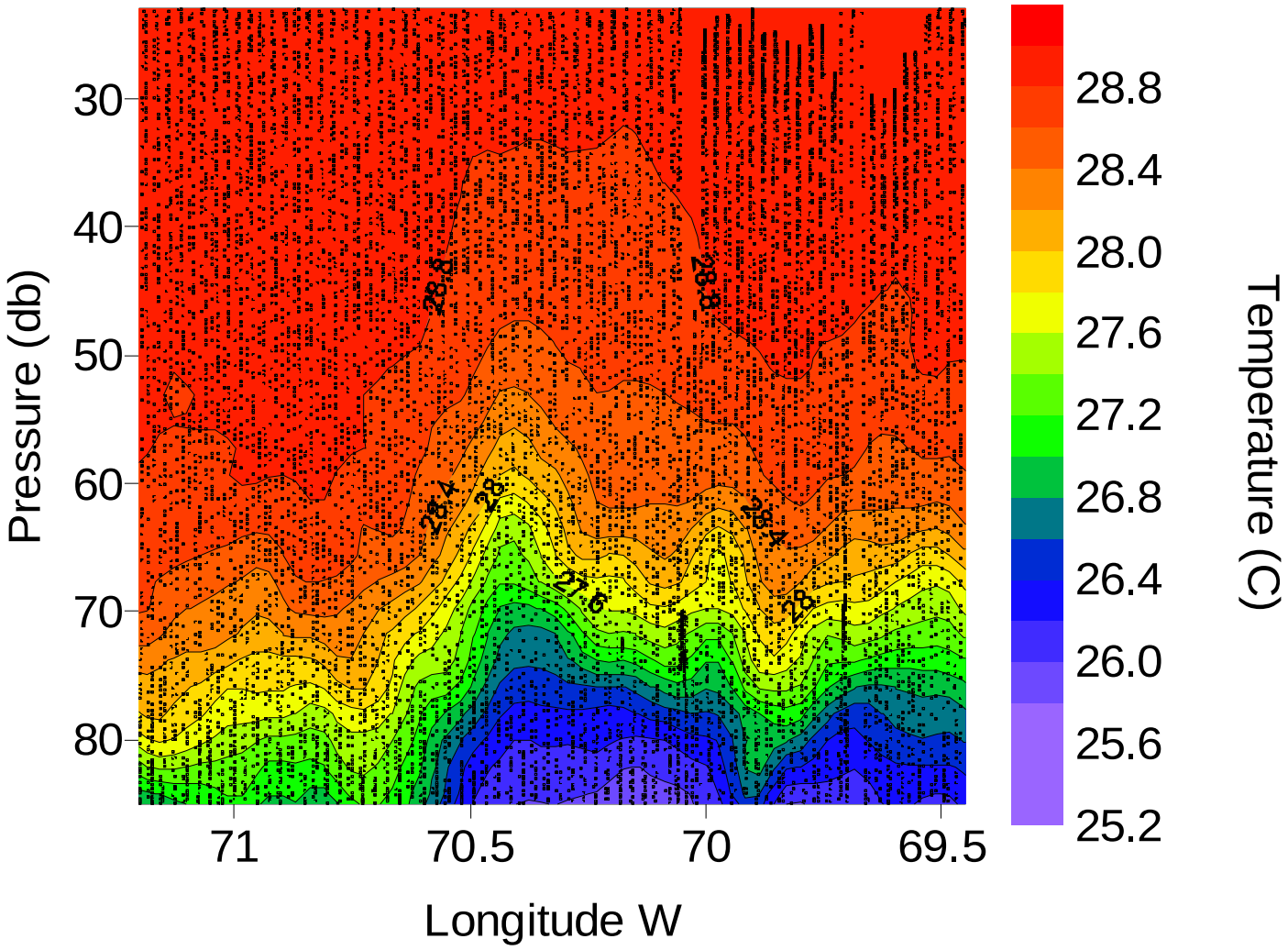

Figure 5. NuShuttle-derived isotherms in upper 90m in cross section from 69.5 to 71.5 W reveals rich detail of upward doming due to upwelling in cyclone. Black dots illustrate the high density of continuous sampling by Underwater Undulating Vehicle.

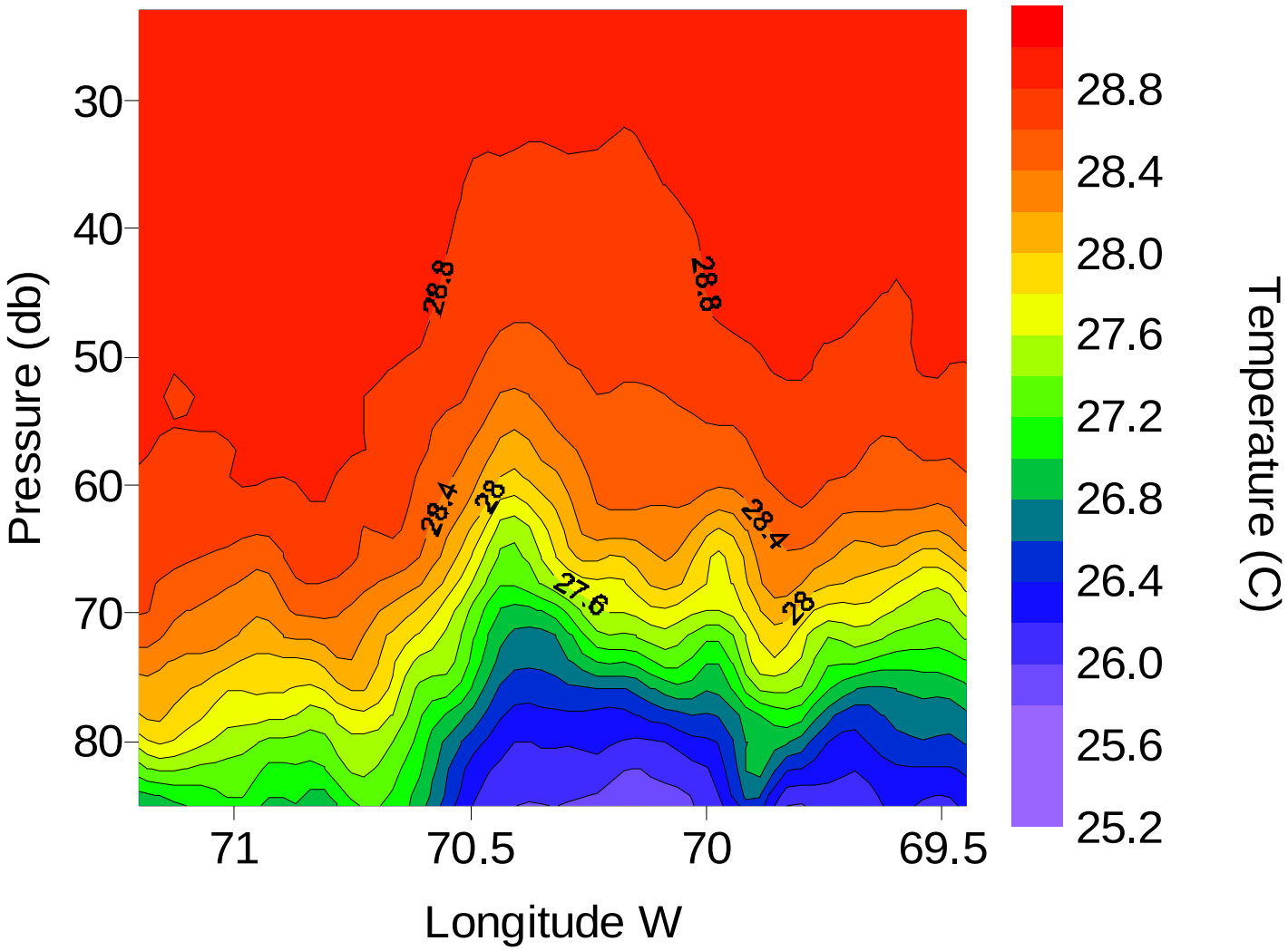

Figure 6. Same as Figure 5 with black dots removed to permit clear view of rich detail show upwelling of 25 deg C water with doming of isotherms of 15 to 25 m excursion.

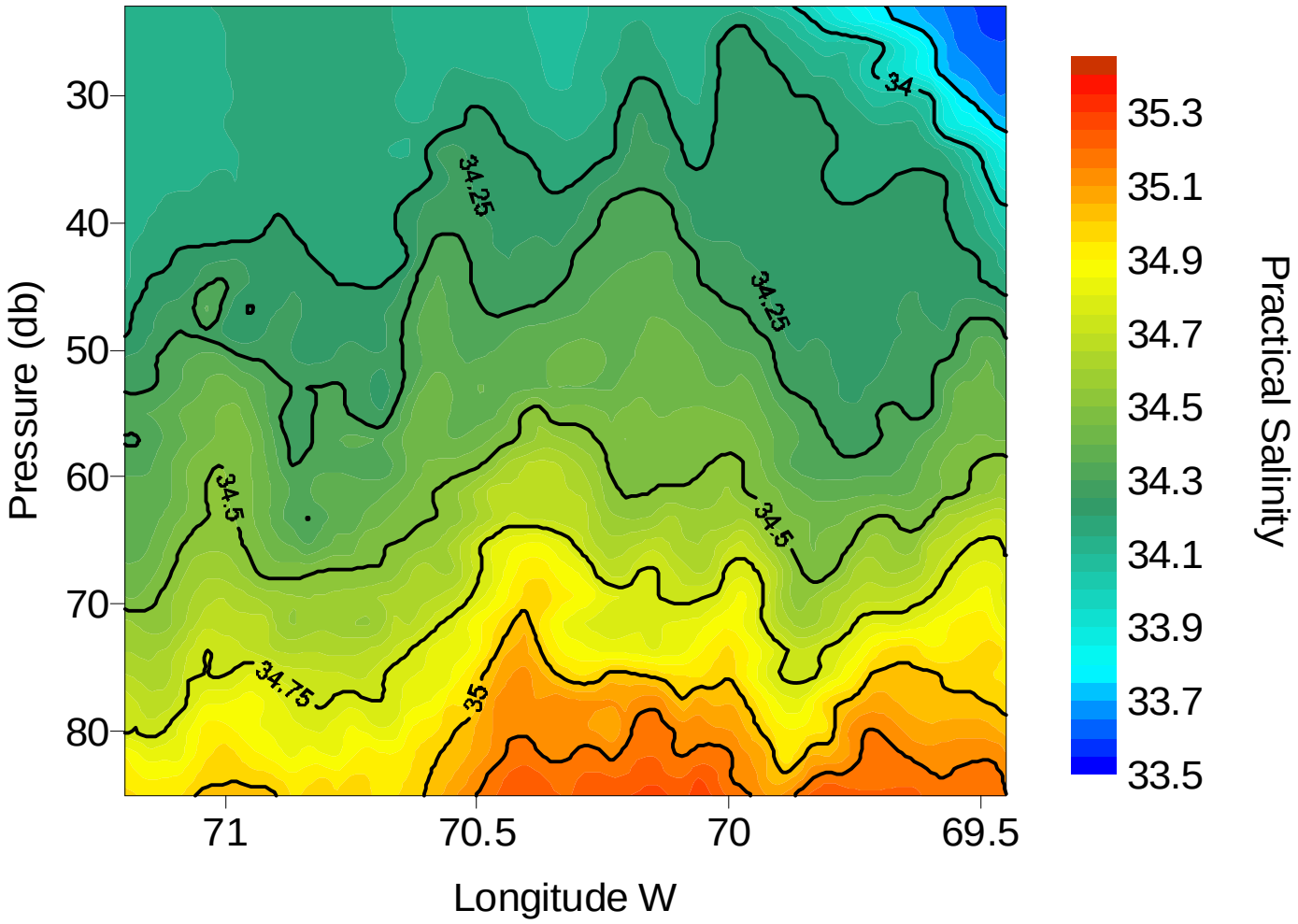

Figure 7. UUV- derived isohaline contours in upper 90m in cross section from 69.5 to 71.0 W reveals upward doming due to upwelling in cyclone of 35 psu water and 33.5 psu in surface.

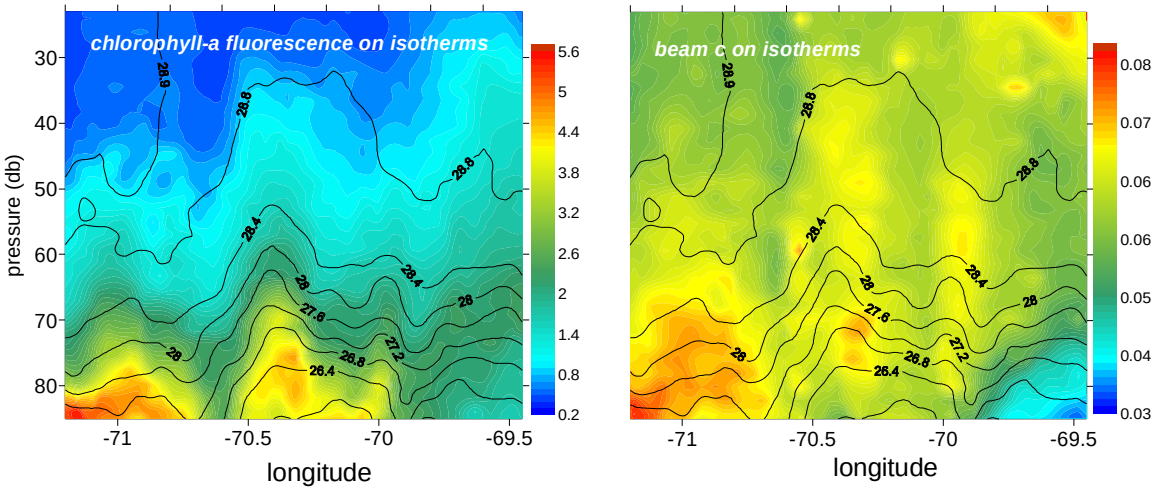

Figure 8. UUV based isotherm contours of upper 90 m overlaid on chlorophyll-a fluorescence color map indicates the widespread occurrence (both within and outside of eddies) of vertical excursions in the 5 to 20 meter range with apparent wavelengths ranging from 4 to 15 km. Often these coincided with localized enhancement of chlorophyll and or decreases in beam attenuation coefficient (c 670).

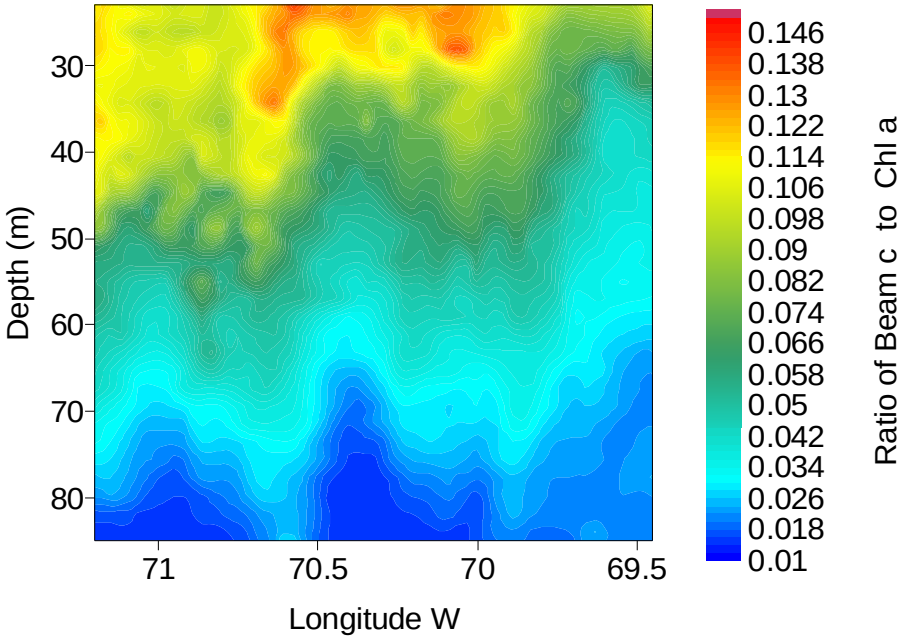

Figure 9. The ratio of Beam c to Chlorophyll-a suggests surface accumulation of non-chlorophyll carbon in the cyclone core. Data indicates the widespread occurrence (both within and outside of eddies) of vertical excursions in the 5 to 20 meter range with apparent wavelengths ranging from 4 to 15 km. Often these coincided with localized enhancement of chlorophyll and or decreases in beam attenuation coefficient (c 660).

E. Eddy pumping results

Apparent nutrient drawdown in a Caribbean Cyclonic Eddy

A fine-scale nutrient sampling pattern at selected isopycnals spanning the euphotic zone was undertaken across the cyclonic eddy depicted in Figure 10 in order to characterize nutrient drawdown attributable to eddy pumping. Our results show unequivocal drawdown of Dissolved Inorganic Nitrogen (DIN), and Dissolved Inorganic Phosphorus (DIP) across the eddy along its displacement path. In order to assess the magnitude of nutrient drawdown across the eddy, limiting calculations to depths above the compensation depth of 169 m, we determine the difference between observed mean concentrations at the two westernmost (presumably unaffected by eddy pumping) and easternmost stations across the eddy dome. We then integrate this across the entire eddy, arriving at total drawdown of 152 and 9 mmol.m-2 DIN and DIP respectively. The drawdown ratio of DIN:DIP was 16.5 denoting a slight preferential DIN uptake over the canonical 15, agreeing with previous arguments of N limitation in the region. Given an eddy diameter of 186 km (deduced from isopycnal displacement) and an average westward displacement speed of 11.6 km-d (deduced from SSHA imagery), and assuming purely Eulerian displacement of the eddy across a static background, we calculate drawdown rates of 9.6 and 0.6 mmole.m-2.d-1 for DIN and DIP respectively, sufficient to sustain a primary production rate of 744-766 mgC.m-2.d-1 assuming Redfield stoichiometry. This rate is substantially higher than rates quoted for waters of the northern ECB 262 mg C.m-2.d-1 but lower than the exceptionally high rates observed, for example, in the upwelling regions of the southern margin of the Caribbean. Apparent drawdown observed was the maximum possible within the eddy as we endeavored to implement the transect across the eddy core where isopycnal lifting is greatest. Since nutrient concentrations increase linearly with depth in the depth range immediately below the euphotic zone, diminished isopycnal lift towards the eddy margin will result in a commensurate depression of euphotic zone enrichment. On the other hand, eddy core SSHA anomalies ranged between -8 and -22 cm, standing at -12 cm during the time of our study. Eddy pumping might have been significantly greater during times of enhanced SSHA.

It is noteworthy that drawdown was incomplete and substantial residual nutrients (52 % DIP 43 % DIN) remained in the euphotic zone following passage of the eddy (station 22). Maximum efficiency of the eddy pumping process rests on the postulate that phytoplankton capacity for nutrient uptake is such that nutrients advected into the euphotic zone are entirely depleted within the time frame of eddy passage; on the order of 23 days in the SNA. Water masses advected from below the euphotic zone are largely devoid of phytoplankton so that seed populations are small. Moreover, greatest enrichment occurs in the deeper zones where light is a limiting factor. Phytoplankton uptake in our study appears to have been insufficient to allow complete nutrient stripping within the time frame of eddy passage, a result anticipated in previous studies. Incomplete drawdown and the uncertainties regarding drawdown across the slope of the eddy disallow estimation of total drawdown. Nevertheless, our results point to significant nutrient drawdown in this eddy.

Uncertainties regarding eddy pumping are due in large part to poor understanding of the underlying physics. Questions regarding net vertical transport of water parcels and hence of nutrient transport into the photic zone remain unsolved. This quandary has been summarized as the degree to which eddy propagation is linear or Eulerian rather than nonlinear or Langrangian. In the latter, a water parcel is trapped within the eddy and nutrient contribution to the euphotic zone throughout the life of the eddy is limited to the content of that water parcel while in the linear case, favored by earlier models all

nitrogen in a theoretical ridge along the eddy track is made available. Larger “ring” structures, with diameters on the order of 500 km such as North Brazil current rings, Gulf of Mexico loop current eddies, Agulhas retroflection rings, and cold and hot core Gulf stream rings all appear to entail entrainment of water masses distinct to those of the eddy-generating current and advection of this parcel across various ocean fronts thus resulting in Lagrangian transport. Advected parcels typically exhibit reduced vorticity relative to an outer more vigorous ring arising from the original meandering current. Of these closed circulation systems, only cold core Gulf Stream rings are cyclonic and thus capable of eddy pumping. Entrainment and advection of a central water mass will significantly reduce eddy pumping as this water mass will be depleted of available nutrients at a time scale on the order of days relative to eddy lifetimes on the order of several months. In these structures, moreover, vorticity decays throughout the lifetime of the ring bringing about decay of the nutrient dome further precipitating the onset of oligotrophy.

Evidence is lacking regarding whether cyclonic eddies with diameters on the order of 200 km exhibit such Lagrangian transport or if, on the other hand, only energy, but no mass is advected laterally and water mass displacement is confined to transitory vertical advection during passage of the eddy. Such latter scenarios are presumed in eddy pumping models yielding highest estimates of photic zone fertilization where eddy passage is viewed akin to wave passage. More conservative, longer term models] take into account the necessary recharging of the subphotic nutrient zone, further reducing fertilization rate estimates.

Such simple models, moreover, portray eddy passage across an immobile background. Caribbean eddies on the other hand transit the region zonally accompanying the net westward transport of the Caribbean current. Surprisingly, average zonal current velocities may exceed net eddy transit rates. Using altimetry data, found that anticyclonic features that appeared near the Beata Rise (73° W) traveled westward into the Colombian Basin at an average speed of 15 cm s-1. Because this is significantly slower than the speed of Lagrangian drifters, they suggest that these features are interacting with the mean Caribbean Current, not being passively advected by it. If this were the case then the nutrient drawdown we observe is in fact due to interaction of the eddy with fresh water masses.

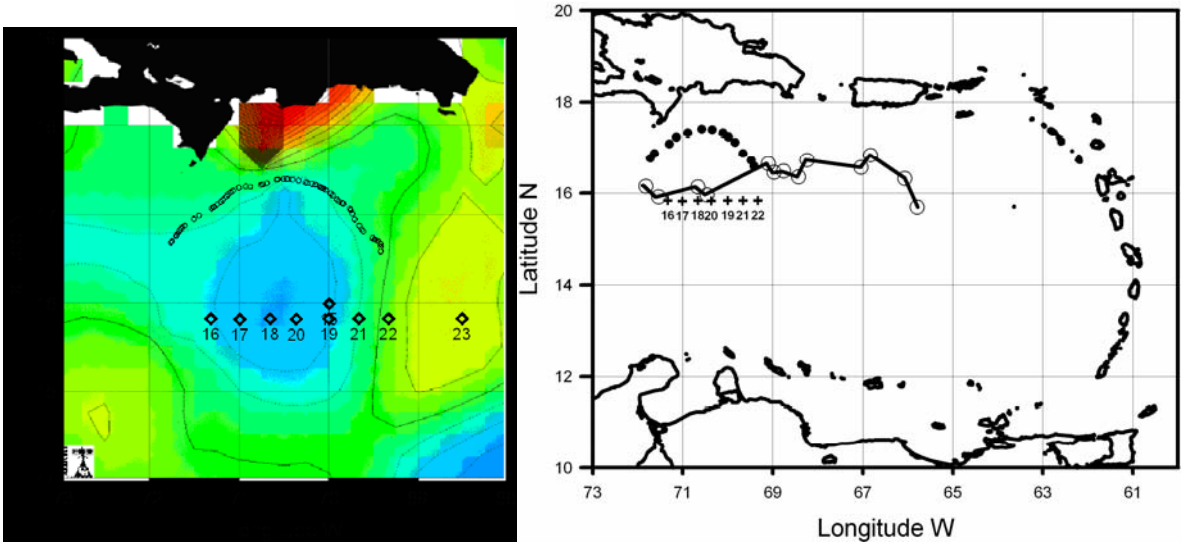
16 17 18 20 19 21 22 23
Latitude N
20
18
16
14
12
10
16 17 18 20 19 21 22
73 71 69 67 65 63 61
Longitude W

Figure 10. Right image shows drifter buoy circling cyclonic eddy. Left image shows eddy trajectory(open circles) as deduced from SSHA, first observation at 15.7o N 65.8o W 6/30/2006, last observation on 9/30/2006; buoy trajectory (closed circles), first observation at 16.9o N 68.68o W on 8/28/2006, last observation on 9/4/2006 and; station positions (crosses) first station on 9/05/2006, last on 9/08/2006.

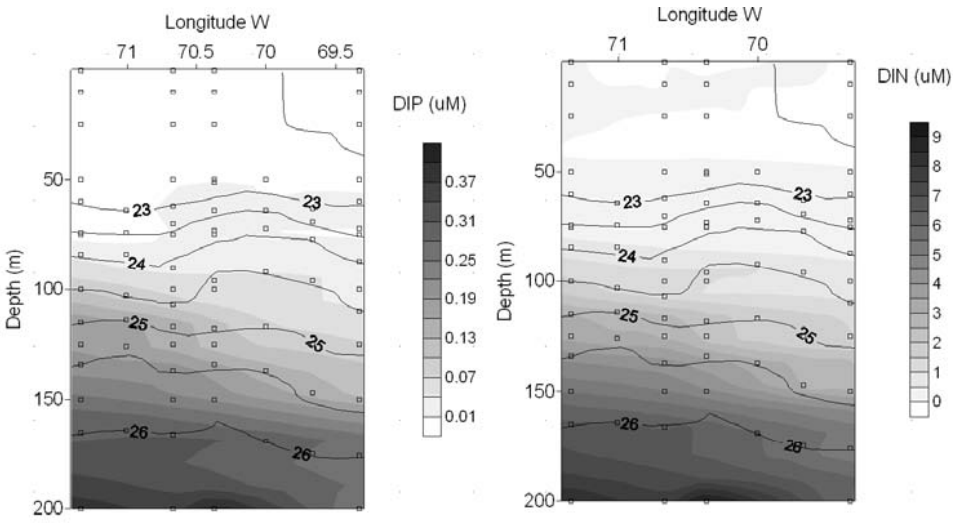

Figure 11. Density and nutrient sections across the cyclonic eddy along latitude 67.8o W. Isopycnals are represented by lines, nutrient fields as grayscale gradients. Left – DIN; right – DIP.

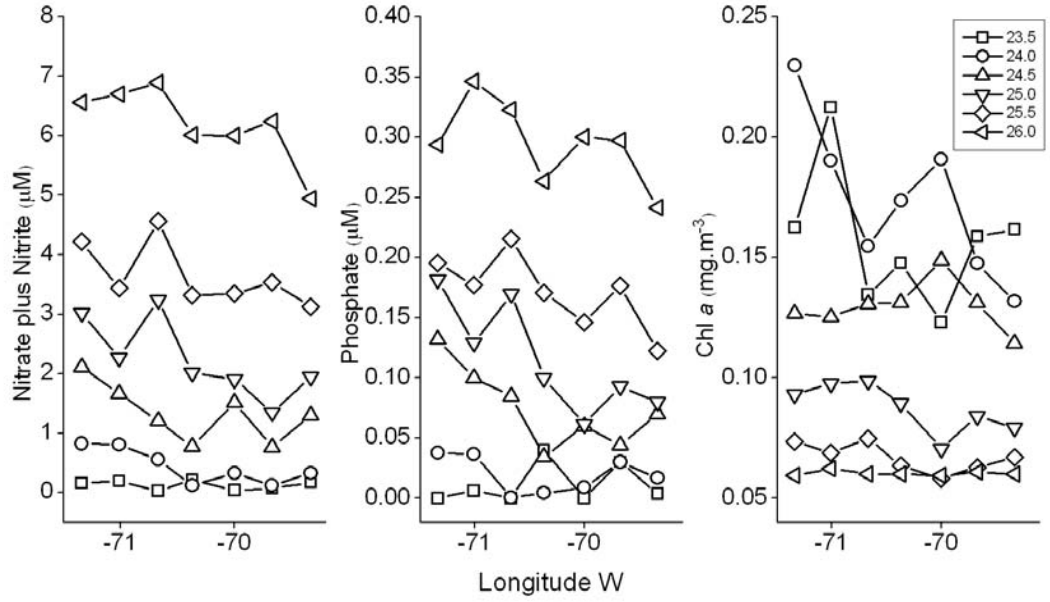

Figure 12. Nutrient loss and phytoplankton response along isopycnals in the transect across the eddy along 15o 50'N. Left – DIN, center – DIP, right Chl a.

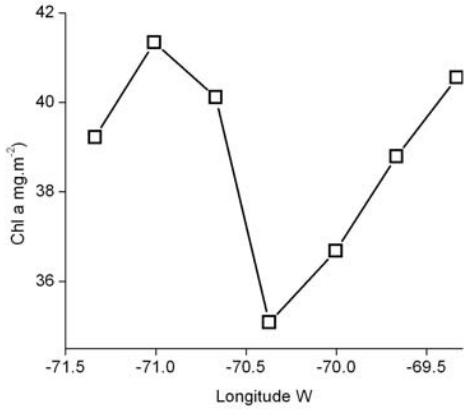

Figure 13. Integrated chlorophyll concentration (mg.m-2) across the cyclonic eddy.

IMPACT/APPLICATIONS

Independent Temperature measurement profiles were made by CTD and XBT casts at nominally 30km horizontal intervals across a cyclonic eddy with nominal vertical resolution of less than 1 m. Meridional plots of eddy cross section from the interpolated data at this resolution show evidence of shallow doming of isotherms (Thermocline Eddy). A much more complex physical and optical structure is revealed by the 1 km horizontal resolution (< 1 m vertical) data obtained with the Undulating Underwater Data Collection System across the same transect of the Cyclonic eddy. Upper water column structure observed through this approach documented intricate excursions (high rugosity of the surfaces) of the upper thermocline, halocline and subsurface chlorophyll maxima beyond that expected from "classical" eddy doming alone. The ratio of Beam c to Chlorophyll-a suggests surface accumulation of non-chlorophyll carbon in the cyclone core. 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 660).

Eddy pumping, a mechanism by which isopycnal doming in cyclonic eddies advects nutrient-rich water into the euphotic zone (EZ), is postulated to fertilize the euphotic zone enhancing phytoplankton production. In order to provide objective data on nutrient drawdown, we followed nutrient content along density surfaces across a cyclonic eddy in the eastern Caribbean Basin. We observed EZ drawdown of 152 and 9 mmol.m-2 dissolved inorganic nitrogen (DIN) and phosphorus (DIP) respectively across the eddy core. Based on an average eddy translational speed of 10 cm.sec-1 derived from satellite altimetry and assuming Eulerian displacement of the eddy across a static background, we calculate maximum possible drawdown rates of 9.6 and 0.6 mmole.m-2.d-1 for DIN and DIP respectively, sufficient to sustain a primary production rate of 766 mgC.m-2.d-1. Nutrient drawdown was however incomplete and residual nutrients (52 % DIP 43 % DIN) remained in the euphotic zone following passage of the eddy.

PUBLICATIONS

Morell J. M., López ,J.M, Méndez, M. and Corredor, J. E., "Optical Signatures of Mesoscale features in the Eastern Caribbean Basin" Poster, XVIII Ocean Optics Meeting, Montreal, Canada, (Oct 9-13, 2006).

López ,J.M, Morell J. M., Capella, J.and Corredor, J. E. "Caribbean Mesoscale Eddies" Poster, Ocean Sciences Meeting, Santa Fe, NM (Feb 8-12, 2007).

Corredor, J. E, Morell J. M. and López ,J.M, "Apparent nutrient drawdown in a Caribbean Cyclonic Eddy" Submitted to Geophysical Research Letters (2007)