“Mesoscale” eddies are large whirlpools in the ocean with diameters of hundreds of kilometers. Their influence can extend to depths of 1000 m or greater. Oceanographers are only now beginning to document the prevalence, extent, and influence of such features in the world ocean. The availability of third-generation ocean color imagery from the Moderate Resolution Imaging Spectroradiometer-MODIS sensors aboard NASA’s AQUA and TERRA platforms, and support for direct observation at sea, have now allowed characterization of such an eddy interacting with the Orinoco River plume (ORP) while traversing the eastern Caribbean basin.

The ORP extends seasonally across the basin from August through November, 3 to 4 months after the peak of the seasonal rains across northeastern South America. At this time, a thin plume of relatively low-salinity water, rich in phytoplankton and bearing significant amounts of colored dissolved organic matter (CDOM) [Blough et al., 1993; Morell and Corredor, 2001], covers a large swath of the basin, offering a striking contrast to the intensely blue oceanic waters of the adjacent northwest Atlantic Ocean.

Ocean color imagery (Figure 1) and sea surface height topography (SSHT) in August 2003 revealed a large circular structure extending 230 km across the eastern Caribbean basin embedded within the ORP. SSHT indicated that the feature was a cyclonic eddy, rotating counterclockwise about its axis, drifting westward at about 7 cm/s.

The Caribbean Vorticity Experiment

The Caribbean Vorticity Experiment (CaVortEx I) was undertaken in August 2003 to characterize the physical, biogeochemical, and optical structure of the eddy and to assess the influence of the eddy and the ORP on biological productivity. Scientists from the University of Puerto Rico characterized surface and subsurface features of the eddy down to 1000 m. The cruise track aboard R/V Chapman transited the eddy core, providing a diametric north-south section (Figure 2) of the eddy. In situ characterization of Caribbean eddies was lacking prior to CaVortEx I.

Density distribution across the eddy (Figure 2a) showed displacements within the eddy core extending to ~700 m, conforming well to observations of cyclonic eddies elsewhere. Shipboard monitoring of near-surface salinity and chlorophyll a (Chl a) concentrations confirmed the horizontal extent of the eddy as visualized in the ocean color imagery (Figure 3a).

Several features particular to the interaction of this eddy with the massive ORP are novel. Salinity structure below ~75 m was as might be expected for eastern Caribbean basin waters; shoaling of the sub-surface, high-salinity, subtropical underwater mass within the eddy core was particularly apparent. Near-surface waters, however, showed influence of the low-salinity ORP with a marked front separating the high-salinity core from surrounding low-salinity ORP waters (Figure 2b). This pattern was reflected in the distribution of dissolved silicate, a nutrient that is abundant in the ORP [Corredor and Morell, 2001], but scarce in surface oceanic waters. High silicate content of near-surface waters in the buoyant plume contrasted with the silicate-poor waters of the eddy core. High-pressure liquid chromatography of surface phytoplankton extracts revealed a phytoplankton community typical of oceanic waters, where cyanophytes are dominant in the eddy core, but a distinct community...
dominated by prasynophytes and diatoms was present in the eddy periphery.

Cyclonic eddies propagating through stratified high-salinity, low-chlorophyll waters such as the “Haulani” eddy off Hawaii [Vailancourt et al., 2003] show shoaling of the deep chlorophyll maximum (DCM) in concert with the vertical water mass displacement. Such “eddy pumping” enhances primary production by bringing nutrient-rich waters into the euphotic zone. The DCM in the Caribbean eddy responds to both eddy pumping and the influence of the buoyant river plume. The DCM in the region shoals considerably in waters influenced by the ORP, reaching depths under 30 m in the east-central Caribbean, in contrast to the greater depths (>90 m) prevailing in the absence of river plume waters and in the adjacent Atlantic [Corredor et al., 2003]. Consequently, while doming of the DCM is apparent in the eddy core, a shallow DCM dominates its periphery. Remnants of the oceanic DCM, presumably diminished by shading, underlie the river-related DCM (Figure 2c).

Optical properties of the cyclonic eddy, measured by profiling radiometry, spectrophotometry, and turbidimetry, were similarly modulated by both the eddy and the river plume. While the oceanic water of the eddy core exhibited low optical absorption and turbidity, nearsurface waters of the surrounding river plume were not only more turbid, they exhibited sharply increased light absorption of the shorter wavelengths (blue and ultraviolet), a property characteristic of high CDOM waters.

A final feature of interest is the distribution of “staircase” patterns across the eddy (Figure 3b). Abrupt discontinuities in temperature and salinity at scales of 10–20 m and intermediate depths (400–600 m), common in the Caribbean [Lambert and Sturges, 1977], are related to double-diffusive processes obeying to differences between diffusive rates of salt and heat. Staircasing was strongest in the mid-eddy shear zone, but was substantially reduced in the eddy core and its periphery. Dynamics of these features in the course of eddy propagation may prove to be significant in the return transport of deepwater masses within the context of the global meridional overturning circulation.

A Spiral in the Eddy

In northern hemisphere cyclonic eddies, Coriolis forcing displaces surface water outwards as deeper waters are transported toward the surface. Such an eddy intersecting a highly colored river plume would displace the buoyant plume waters and traverse the plume intact. It would appear from space as a coherent disk of clear water within the turbid surface plume. High-resolution MODIS imagery, however, reveals a distinct filament of ORP water spiraling within the eddy core, a feature replicated in surface transects appearing as localized, low-salinity and high-chl a anomalies within the eddy (Figure 3a). Anticyclonic (rotating clockwise) Caribbean eddies are thought to originate from Atlantic Ocean eddies known as North Brazil Current Rings (NBCR), which are generated by instabilities in the NBC retroflection [Johns et al., 1990]. Following impingement on the island arc of the Antilles, some NBCRs, particularly the weaker, larger rings, appear to be able to squeeze through the island passes and re-form within the island arc with little loss of mass [Simmons and Nof, 2002]. Genesis of Caribbean cyclonic eddies is less clear, but may follow a similar path, and the entrained spiral filament may result as a consequence of eddy reformation.

Caribbean Eddies

The rich eddy field of the Caribbean is depicted in data-assimilative model products available at http://www7300.nrlssc.navy.mil/global_mion/global_mion/ias.html and www7320.nrlssc.navy.mil/IASNSF_WWW/today/IASNSF_ias.html. Eddy trajectories in the Caribbean have been directly observed by deployment of Lagrangian drifters, and details of their apparent height and periodicity derived from SSH are available. Although Murphy et al. [1999] have remarked that Caribbean eddies are primarily anti-cyclonic, other analyses [Carton and Chao, 1999] indicate that cyclonic and anti-cyclonic pairs are also formed through interaction with the island masses of Trinidad and Tobago. Caribbean eddies have been implicated in ventilation of the Cariaco basin [Astor et al., 2003], ichthyoplankton transport, and the safety of oil and gas exploration structures.

Continued investigation will provide additional information on their effects on biological processes, on their contribution to large-scale ocean circulation, and on their variability in response to global change. Spaceborne ocean color imagery has proven to be a powerful tool for characterizing such complex interactions; it provides detail unattainable with traditional shipboard techniques or with other remote sensing products such as SSH.
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Fig. 3. (a) The horizontal distribution of near-surface salinity and Chl a across the eddy is shown (14–15 August 2003). GPS-referenced data were obtained by means of a shipboard continuous sea water pumping system, a thermosalinograph, and a chlorophyll fluorometer Real-time shipboard salinity and chlorophyll a measurements across the track closely reflect the pattern observed in the satellite imagery. Arrows point to transient salinity and Chl a anomalies associated with the spiral of ORP water entrained in the eddy. (b) Temperature “staircasing” in the eddy; the well-formed staircase structure is apparent at 15°20'N in the eddy shear zone, but is absent in the eddy core at 14°50'N.