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Eddy development and motion in the Caribbean Sea

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Abstract. Eddy motion in the Caribbean Sea is described on the basis of sea level anomalies deduced from ERS-1 altimetry data corrected with TOPEX/Poseidon data during the 15 months of the Exact Repeat Mission (October 1992 to December 1993). Both cyclones and anticyclones were observed in the satellite data as anomalies originating in the Venezuelan Basin or entering the Caribbean through the Antillean passages, mainly the St. Lucia Channel, Anegada Passage, and north of Trinidad. The diameter of the eddies ranged from a few tens of kilometers to 700 km. Advection speeds were typically 20-30 cm s^{-1} and the eddies were energetic (kinetic energy > 0.6 m^2 s^{-2}). Their lifetime of 3-4 months was determined, in general, by their interaction with topography. Most eddy activity was eroded and disappeared at the Central American Rise area, although a few eddies crossed into the Cayman Sea through the Chibcha Channel. Some eddies also entered the Cayman Sea from outside the Caribbean through the Windward Passage. The Panama-Colombia Gyre was evident only during the tropical rainy season. A large cyclonic eddy was formed there during the period of maximum precipitation, when strong meridional salinity and wind speed gradients occurred. Eddy production in the central Caribbean appears to be associated with the interaction of the meandering Caribbean Current and the strong wind curl.

1. Introduction

The Caribbean is a semienclosed sea surrounded by the landmasses of South and Central America and separated from the Atlantic Ocean by the islands, banks, and sills of the Antilles Islands Arc. It spans over 3500 km of longitude and ~2500 km of latitude. The Caribbean Sea has three major parts: the eastern Caribbean north of Venezuela, the Cayman Sea in the west, and the southwestern Caribbean Sea bounded by Colombia and Central America (Figure 1a).

In terms of bottom topography the Caribbean Sea can be divided into a series of five basins (Figure 1b). The Grenada Basin lies between the Lesser Antilles Arc and Las Aves Ridge, while the Venezuelan Basin lies between the Las Aves and Beata Ridges, and the Colombian Basin lies between Beata Ridge and the Central American Rise. The Cayman Basin is the area between the Central American Rise and the Cayman Ridge. Finally, the Yucatan Basin lies between the Cayman Ridge and the Yucatan Strait where the Caribbean ends. This topography is an important factor in the generation and modification of eddies [*Molinari et al.,* 1981].

The climate of the region is modulated by the geographical position of the Intertropical Convergence Zone (ITCZ). The seasonality of the position of the ITCZ corresponds to the windy and dry (December-April) and rainy (August-October) seasons. The rest of the year is transitional between these two seasons (Figure 2). In the dry season the ITCZ resides at its southernmost position (0-5°S). At that time the northern trade winds dominate the area with average speeds of ~8 m s^{-1} and diurnal peaks of up to 15 m s^{-1} [*Andrade*, 1993].

In July, following the onset of the rainy season, a particular situation arises when the northeasterly trades increase, temporarily inhibiting the increasing precipitation rate of the area. This is the so-called "Veranillo" or "midsummer drought" [*Variability of American Monsoon Systems,* 1998]. During the rainy season proper the ITCZ moves over the southwestern Caribbean, decreasing the wind speed of the southerlies there and promoting the highest rate of precipitation anywhere around the globe. At the same time, higher speeds of the trade easterlies are attained in the central Caribbean Sea. The rest of the Caribbean is drier throughout the year with significant precipitation localized in each island to the windward sides of mountain slopes [*Gray,* 1993].

Surface circulation in the region consists of a generalized westward flow called the Caribbean Current. This circulation exhibits much temporal and spatial variability, such as synoptic mesoscale eddies [*Kinder et al.,* 1985]. Mesoscale variability of the Caribbean has been related to "eddy waves" [*Johns et al.,* 1990]. These are generated by mesoscale features originating from the North Brazil Current Retroflection in the form of anticyclones impinging on the Lesser Antilles passages [*Fratantoni et al.,* 1995]. These mesoscale eddies and meanders with sizes of 100-500 km travel along the Caribbean Current axis [*Fu and Holt,* 1983]. Moreover, in the northeastern Caribbean, fluctuations have been noted to be stronger than the mean currents [*Molinari et al.,* 1981]. Anticyclonic gyres of ~200 km diameter traveling with westward at 30 cm s^{-1} in the northern Caribbean were reported by *Nystuen and Andrade* [1993], who also detected a persistent cyclonic circulation in the southwestern part of the basin on different occasions.

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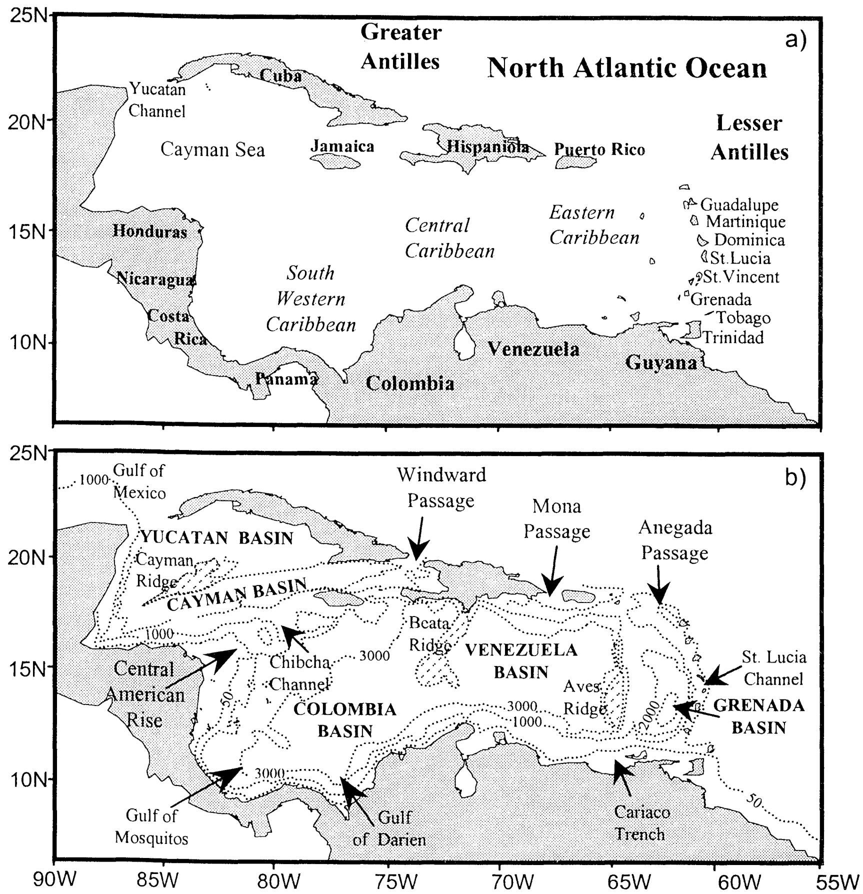

Figure 1. The study area showing important geological and geographical features: (a) the dotted areas are shallower than 50 m and (b) isobaths are labeled. Shadowed areas represent ridges shallower than 1000 m.

Simulations using the U.S. Navy Layered Ocean Model [*Wallcraft*, 1991] (a 1/4° resolution model with a 5.5-layer reduced gravity and a six-layer model with realistic bottom topography, having an explicit numerical scheme for the reduced gravity, formulated using an Arakawa "C" grid) by *Murphy et al.* [1999] indicated eddy motion penetrated the Lesser Antilles and propagated across the Caribbean in ~2 months. Similar eddies can form by horizontal shear instability in two-layer and reduced gravity models [*Heburn et al.*, 1982] and can also be produced when eddies from the North Atlantic Ocean impinge on the Lesser Antilles as in the model of *Capella* [1994].

Surface flow of the southwestern Caribbean Sea in recent numerical simulations showed a broad cyclonic circulation, which was labeled the Panama-Colombia Gyre [*Mooers and Maul,* 1998]. This is a complex structure made up of an intense cyclone, plus an adjoining anticyclone and cyclone all embedded in the larger but weaker cyclonic circulation. This "triad" of mesoscale gyres is thought to interact with the shelf waters offshore of Panama, Colombia, and Venezuela. The portion of the cyclonic motion along the coasts of Panama and Colombia is also known as the Darien Countercurrent.

This paper will focus on describing the oceanic mesoscale circulation from the combined ERS-1 and TOPEX/Poseidon data set for the period when they were flying simultaneously, i.e., October 1992 to December 1993, in an exact repeat mission with cycles of 35 and 10 days, respectively. For the first time, tracking both cyclonic and anticyclonic eddies during their entire lifetime within the region, showing eddies entering through different passages to the Caribbean, and demonstrating merging of eddies of different origins has been possible.

2. Methodology

The merged data set used in this study was produced by the European Space Agency, which provides a sea level anomaly (SLA) calculated relative to a mean. The ERS-1 data have been adjusted onto the more precise TOPEX/Poseidon data using a global minimization of ERS-1 and TOPEX/Poseidon dual crossovers. This combination allowed a mapping of the surface ocean variability with high accuracy and improved spatial and temporal coverage [*Le Traon et al.*, 1995]. Correlation coefficients for combined ERS-1 and TOPEX/Poseidon maps with hydrographic data were found to be above 0.85 in the worst cases [*Hernandez et al.*, 1995].

The SLA file was generated using the repeat track analysis method. Data were first validated, and all altimetric corrections were applied [including inverse barometer correction and orbit error correction] to compute the corrected sea surface height. For a given track and for each cycle, data were then resampled every 7 km using a cubic spline, and anomalies relative to the mean over all available cycles were calculated [*Le Traon et al.*, 1995].

The way in which ERS-1 covered the area allows the generation of two maps corresponding to the first and second halves of the cycle. The area is swept in the first 17.5 days with ground track separation of 160 km. The sampling is then repeated in the second half cycle at the same ground resolution but offset by half the ground track separation. This halves the spatial resolution between tracks but can smear features that move substantially in half a cycle. By generating two contour maps in each 35 day cycle, better temporal resolution and better feature tracking are obtained, albeit at the expense of spatial resolution. The data over the Caribbean were gridded for every 17.5 days in half degree of latitude by half degree of longitude bins using the minimum curvature method [*Smith et al.*, 1997] to perform smooth interpolation to the irregularly spaced data.

Comparison of contour maps of the data set for complete cycles, for half cycles, and for TOPEX-Poseidon cycles demonstrated that the mesoscale features of interest here were defined adequately by the half-cycle data. Our results are therefore presented as contour maps every half Exact Repeat Mission cycle (~18 days) to improve the time sequence and describe the evolution of the mesoscale activity in greater detail. The ground track orbit density of one half cycle ERS-1 over the Caribbean is enough to assure a detailed coverage of the basin (Figure 3). The contour maps were used to define eddy trajectories and to calculate eddy momentum and energy assuming synopticity [all data taken at the same time] in each contour map.

Geostrophic velocity was calculated from the SLA at each grid point from:

$$u = -\frac{\mathbf{g}}{f}\frac{\partial \eta}{\partial y}, \qquad v = \frac{\mathbf{g}}{f}\frac{\partial \eta}{\partial x}$$

using centered differences, where η is the sea level, u and v are the velocity components, f is the Coriolis acceleration, and $\mathbf{g}$ is the gravitational acceleration. Eddy kinetic energy,

$$K = \frac{u^2 + v^2}{2}$$

enstrophy,

$$< k >= \frac{1}{2}\left(\nabla \times V\right)^2$$

and wave number modulus,

$$< w >= \left(\frac{< k >}{K}\right)^{1/2}$$

were calculated at every gridpoint and averaged for the two Caribbean seasons.

The mean sea level signal of the Caribbean was lost in the procedure for obtaining the SLA from ERS-1 altimetry data. In

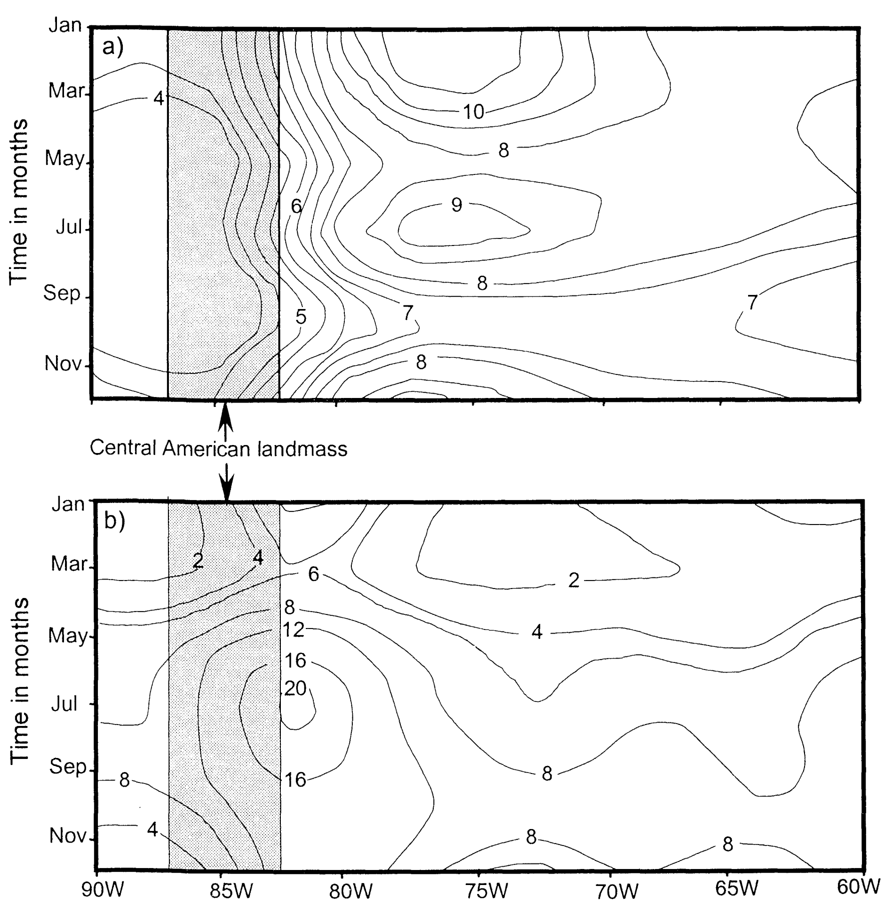

Figure 2. National Center for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) reanalysis atlas [*Climatic Diagnostic Center*, 1998], downloaded at (www.cdc.noaa.gov), (a) monthly means of wind speed (m s^{-1}) and (b) precipitation rate (10^5kg m^{-2} s^{-1}) at latitude 14°N, plotted as a function of date and longitude. Note that the strongest wind period between December and April alternates with highest precipitation rates across the Caribbean. Maximum precipitation and weak winds occurs over the Caribbean coast of Central America year-round.

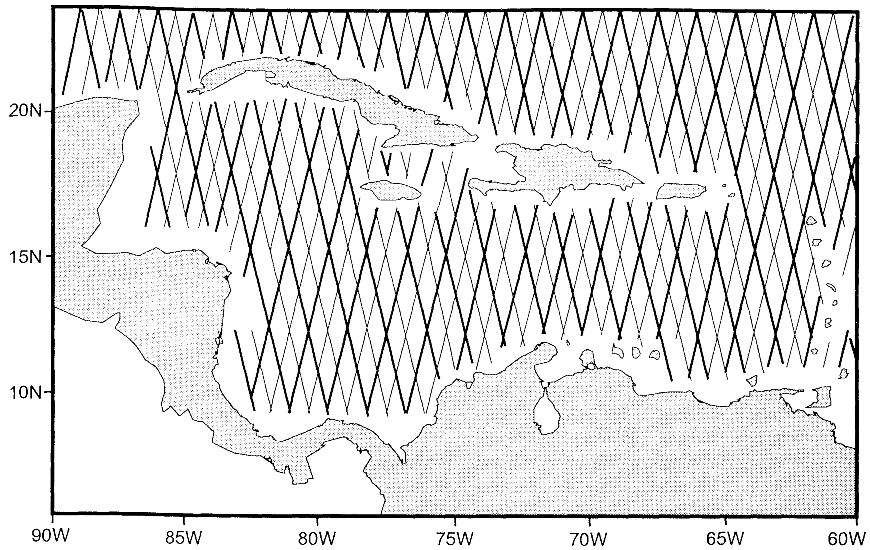

Figure 3. ERS-1 ground tracks over the Caribbean for the first [thinner lines] and second halves of the 35 day cycle during the Exact Repeat Mission.

an attempt to recover it the dynamic height was calculated for every month from historical data in the *Ocean Climate Laboratory* [1994] at every degree of latitude and degree of longitude intersection and then subdivided in a grid of 0.5° to add to the corresponding satellite data.

Root mean square sea level, eddy kinetic energy, enstrophy, and wave number modulus over the Cayman Sea and Venezuelan and Colombian Basins were calculated, and normalized over each area. High values of enstrophy will show where the vorticity is higher on average, independent of the sense of rotation.

The data set used in the present study permitted the analysis of these variables in the Caribbean Sea over a continuous period of 15 months. Prior to this study, mesoscale features had been tracked only during short periods of time [*Nystuen and Andrade,* 1993] because navigational difficulties with Geosat interrupted the data record.

3. Sea Level Variability

Significant sea level variability could be tracked through the SLA contour maps for every half cycle [17.5 days]. Contour maps are referred to by the central date of every half cycle. Contours of eddy anomalies were identified by visual inspection and tracked sequentially to observe their movement

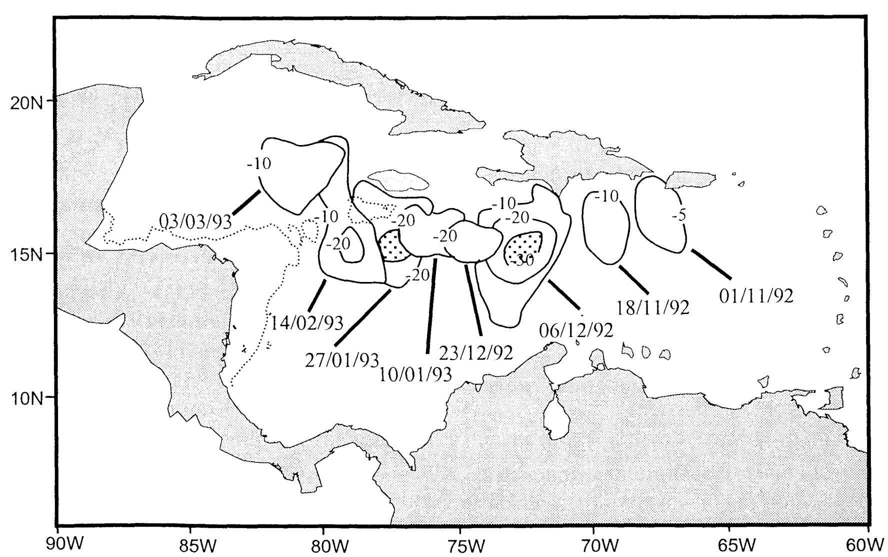

Figure 4. Contours of sea level in centimeters (dotted areas are <-30 cm) in different times. The sequence shows the evolution of a cyclonic eddy that entered the Caribbean through the Anegada Passage or formed south of Puerto Rico in November 1992. It developed maximum intensity (<-30 cm anomaly) over the Beata Ridge in the Central Caribbean and again south of Jamaica, then deformed and weakened, passing to the Cayman Sea in March 1993.

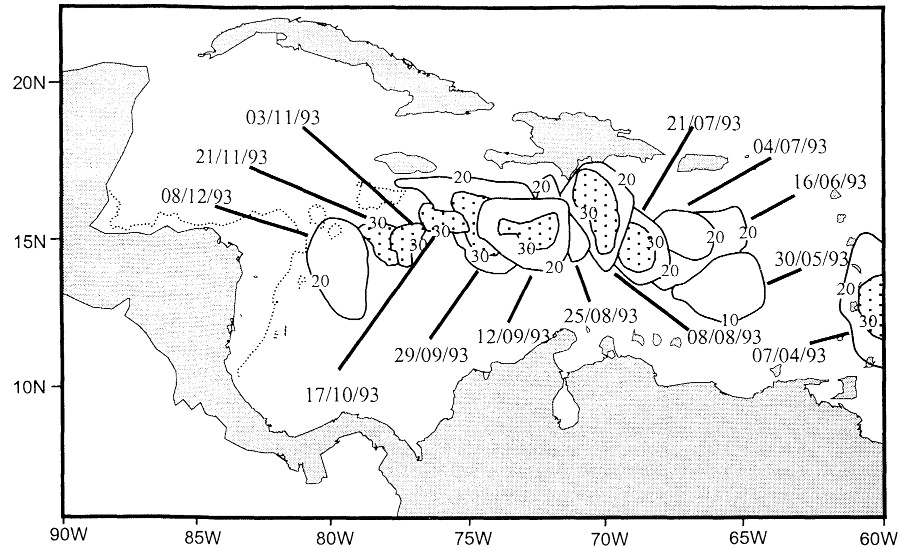

Figure 5. Contours of sea level in centimeters (dotted areas are >30 cm) in different times. This sequence shows the evolution of an anticyclonic eddy that was observed outside the Lesser Antilles in April 1993, entered the Caribbean, and strengthened as it traveled across the northern Caribbean until December 1993, when it disappeared on interaction with the shallows of the Central American Rise.

and strength as a function of time (animated sequences of SLA maps were useful in this respect). However, bear in mind that the altimetry tracks do not always sample the center of the features, so apparent changes in intensity are probably only realistic when observed in a sequence of maps. The most prominent and long-lived mesoscale features, three cyclonic and two anticyclonic eddies, are described below, though numerous other eddy structures appeared for short sequences of maps. The diameter of the eddies was roughly defined by the diameter of the largest recognizable contour enclosing the feature. In Figures 4-9, only selected contours are shown for reasons of clarity.

A negative anomaly (cyclonic eddy) was detected inside the Caribbean close to Puerto Rico in November 1992, probably having entered through the Anegada Passage (Figure 4). As it was advected through the central Caribbean, it appeared to undergo intensifications in two locations. The first increase was evident on December 6, 1992, when the eddy passed over Beata Ridge (70°W) reaching an anomaly in excess of 30 cm in its center. The second was on January 27, 1993, when it was south of Jamaica (78°W). At the latter location, interaction occurred with the currents and with SLAs emerging from the Jamaica-Hispaniola Channel, a site of enhanced wind speed. However, as the second strengthening appeared in only one mapping, it might reflect sampling noise rather than a real increase.

On February 14, 1993, the SLA weakened and deformed as the eddy crossed the sill of the Central American Rise (the

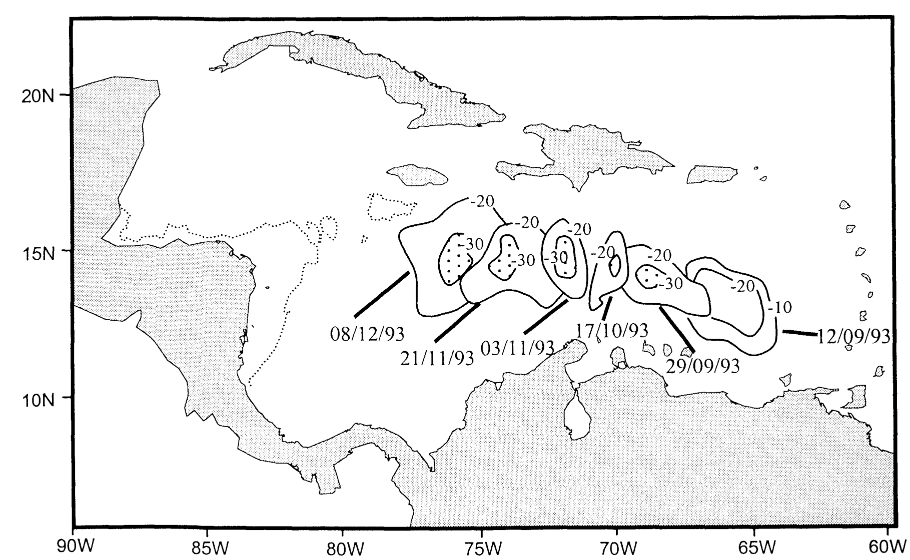

Figure 6. Contours of sea level in centimeters (dotted areas are <-30 cm) in different times. Track of a cyclonic eddy that formed off the Venezuelan coast or entered the Caribbean from the Lesser Antilles in September 1993 and intensified as it traveled across the sea. It was tracked until the end of the data set in December 1993.

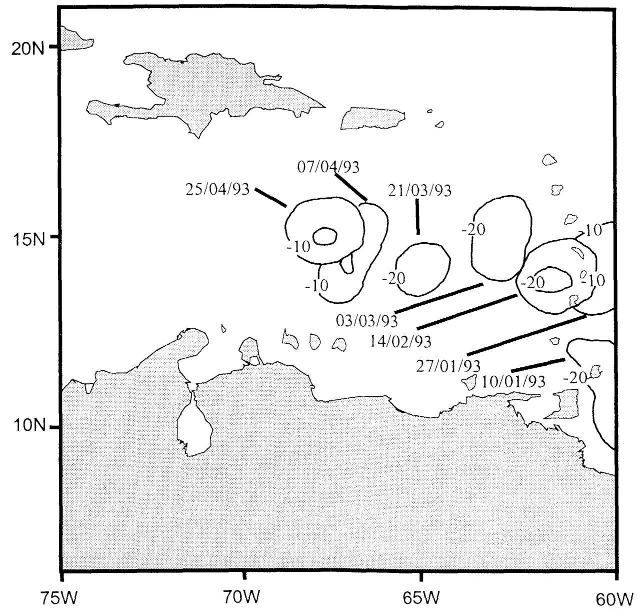

Figure 7. Evolution of a cyclonic eddy observed initially traveling northward outside the Lesser Antilles. It entered the Caribbean through the St. Lucia Channel and traveled across the Eastern Caribbean.

Chibcha Channel between Pedro and Serranilla Banks, in Figure 1b). It was detected only once more, on March 3, 1993, in the Cayman Sea, as a weak cyclonic anomaly.

An anticyclonic eddy (positive anomaly) was detected outside the Lesser Antilles around April 7, 1993 (Figure 5). One month later, the relatively weak anomaly (~10 cm) was detected inside the basin, becoming stronger as it moved across the northern part of the central Caribbean. On reaching the shallows of the Central American Rise, it turned south and appeared to weaken through interaction with topography at the end of the observation period in early December.

Another cyclone was detected on September 12, 1993, in the Southeastern Caribbean (Figure 6). It traveled westward, increasing in diameter from ~200 km initially to 500 km by the time it arrived in the central basin. It was tracked until the end of the data set in December 1993, when it was still showing no sign of decay.

A third cyclonic eddy was detected on January 10, 1993, as a strong negative anomaly traveling northward outside the Lesser Antilles (Figure 7). It entered the Caribbean through the St. Lucia channel on February 14, 1993, and commenced its journey through the basin like the other features described above. It was tracked until April 25, 1993, when it disappeared south of Puerto Rico. The apparent cause of this disappearance was its interaction with the anticyclonic eddy of Figure 5, which overtook it during that period.

An anticyclone was detected in the Windward Passage on May 25, 1993 (Figure 8). It was not observed previously outside the Caribbean, so may have formed by interaction with topography in the passage. However, its relatively weak anomaly may simply have remained undetected until it strengthened on entering the Caribbean. It crossed the Cayman Sea between Jamaica and Cuba and traveled slowly westward through the Yucatan Basin to pass intact through the Yucatan Channel into the Gulf of Mexico 6 months later, in November 1993. This was the only eddy of the five discussed above seen to enter the gulf, but many smaller and shorter-lived structures did appear to do so.

From July to November 1993, sea level contour maps showed the spectacular formation, evolution, and dissipation of a large mesoscale eddy and its interaction with a smaller companion in the southwestern Caribbean Sea (Figure 9). On August 8, 1993, a cyclonic feature became apparent in the southwestern Caribbean at the same time as a smaller cyclonic anomaly in the Caribbean Current appeared north of Colombia. By August 25 the larger eddy had intensified and moved eastward to approach the smaller cyclone moving west (Figure 9a). By September 12, 1993, the two negative anomalies traveling in different directions began merging off the Colombian coast (Figure 9b).

By September 29, 1993 (Figure 9c), they formed one cyclone with a relatively strong signal of -30 cm height anomaly and 500 km diameter off the Colombian continental shelf. On October 17, 1993, when it reached ~15°N (Figure 9d) the eddy turned westward and was advected westward for 7 weeks until it reached the Central American shelf and banks. At this time, the eddy formation process was evidently being

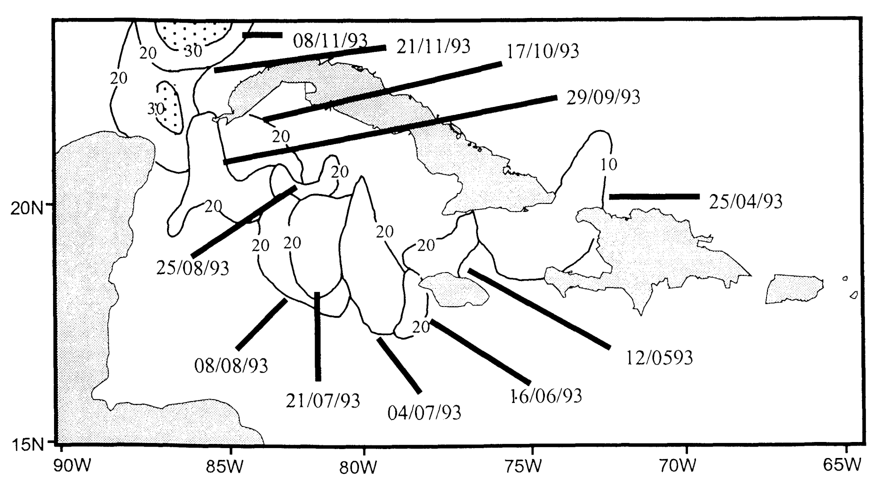

Figure 8. Contours of sea level in centimeters (dotted areas are >30 cm) in different times. The sequence shows an anticyclonic eddy that entered the Caribbean through the Windward Passage in April 1993 and increased in strength as it slowly crossed the Cayman Basin to exit through the Yucatan Strait into the Gulf of Mexico in November.

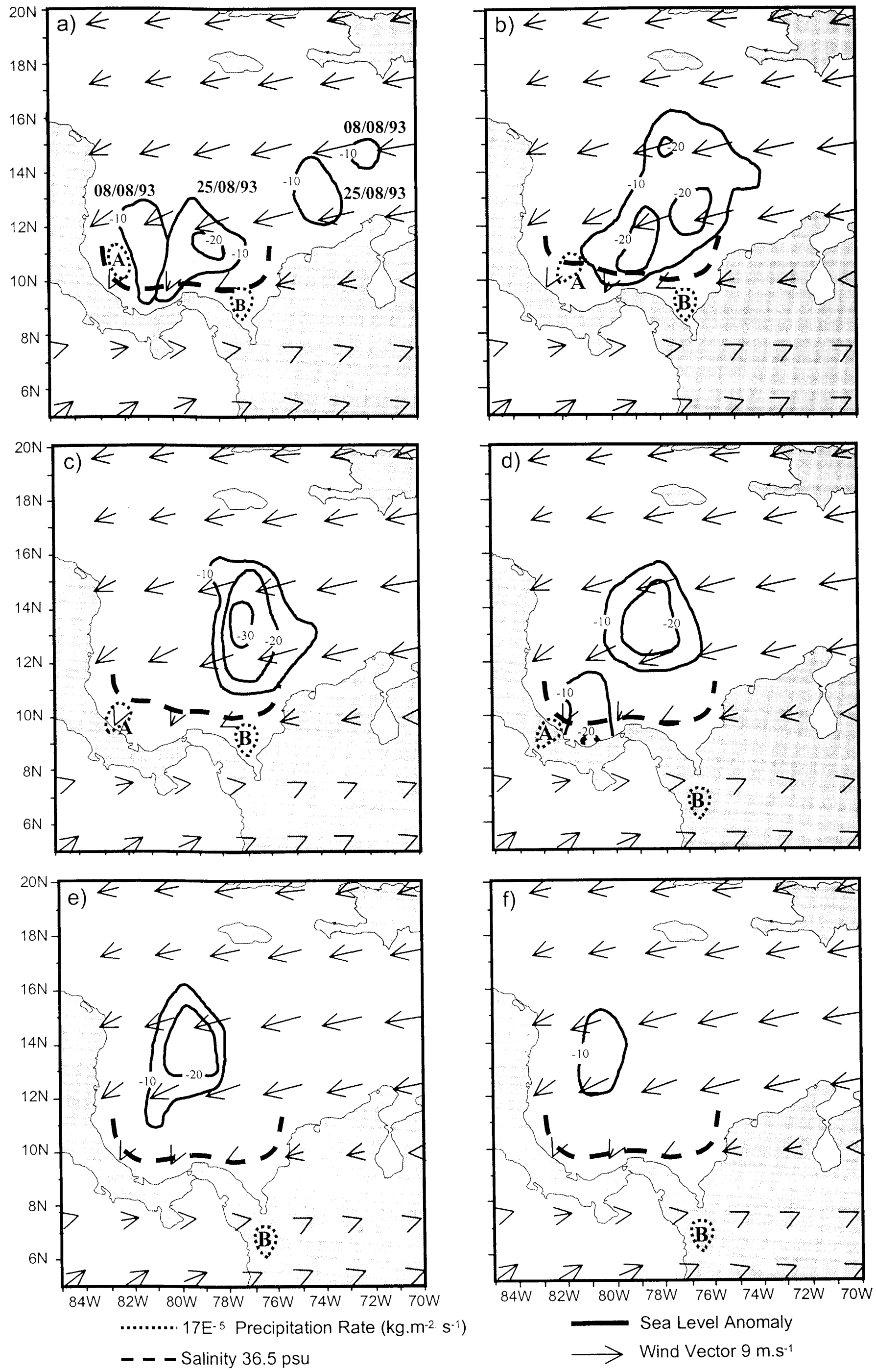

Figure 9. Sea level anomalies for features observed on (a) August 8 and August 25, (b) September 12, (c) September 29, (d) October 17, (e) November 3, and (f) November 21, 1993, superimposed on *Ocean Climate Laboratory* [1994] corresponding monthly mean 36.5 practical salinity units (psu) sea surface salinity and *Climate Diagnostics Center* [1998] monthly mean wind vectors and maximum precipitation rate contours A and B. The sequence shows the formation and evolution of a cyclonic eddy in the Southwestern Caribbean Sea. It merged from two cyclonic eddies (Figure 9a), which deepened as they approached each other to form a single stronger feature in October. The eddy moved westward while weakened and dissipated against the shallows of the Central American Rise. Note the strong meridional wind gradient in the southwest and the position of the precipitation maximum related to the origin of eddy cyclones.

repeated as another cyclonic eddy appeared in the southwestern most corner of the area, close to the southward shifted precipitation maximum. The first merged eddy disappeared rapidly after reaching the shallow rise on November 3, 1993 (Figure 9e). The overall eddy movement in the southwestern Caribbean appeared to follow a larger scale cyclonic circulation. This regime appears to be related to atmospheric conditions of wind forcing and intense precipitation in the area.

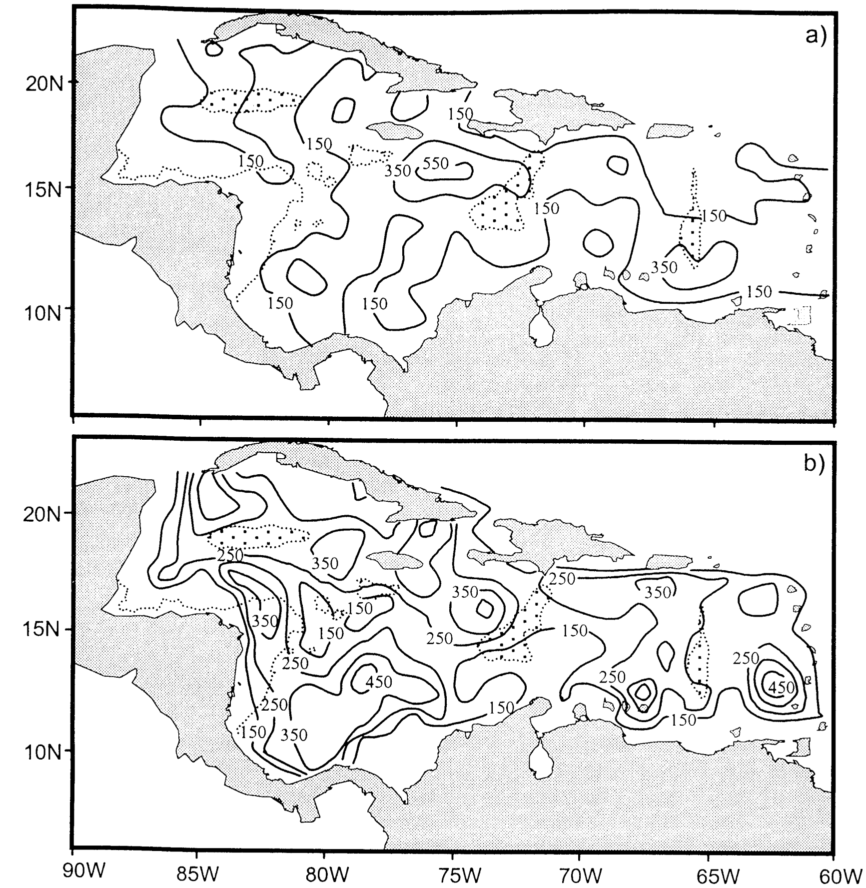

Figure 10. Rms (in mm) from ERS-1 SLAs in the Caribbean Sea for (a) the windy season and (b) the rainy season. Variability was highest in the basins and seemed reduced over the ridges (shaded). It was higher in the rainy season especially west of St. Lucia, west of Beata Ridge, and east of Chibcha Channel.

The change in wind direction across the ITCZ and the salinity gradient resulting from dilution in the southwest may play a role in the formation of both the general cyclonic circulation and the individual eddies incorporated in it. As the eddies move eastward and northward with the Darien Countercurrent, they eventually enter the region of strong westward wind where they then are advected westward by the Caribbean Current toward the Central American Rise (Figure 9f).

On the basis of the eddies described above, and numerous others not explicitly described, some general results emerge. Eddies not formed in the southwest appeared to enter the Caribbean through Anegada Passage, St. Lucia Channel, and Windward Passage and to exit the basin through the Chibcha Channel to the Cayman Sea and through the Yucatan Channel to the Gulf of Mexico. Some eddies never leave the Caribbean but break up and disappear on encountering the Central American Rise. The largest cyclones and anticyclones, apart from those formed in the southwestern basin, traveled along paths north of 14°N. Activity south of 14°N appeared to be generally limited to smaller than mesoscale.

4. Variability Between Basins

During the tropical windy season (the boreal cold season of November to April) the root mean square (rms) sea level showed maximum variability in the central Caribbean, in the northern Colombian Basin (Figure 10a). Variability was high in the eastern Venezuelan Basin and in a small area of the southwestern Caribbean. During the rainy season (the boreal hot season of June-October), rms sea level was higher in general (Figure 10b). Maxima of variability were located in an extended portion of the southwestern Caribbean, the Yucatan Basin, and the central Caribbean as well as in the southeast. The variability seemed to be related to topographic features, being generally higher in the basins and lower over ridges, though the eddy in Figure 4 was enhanced at Beata Ridge.

Kinetic energy was calculated at every gridpoint, assuming geostrophy and spatial stationarity, and was contoured for the two tropical seasons (Figures 11a and 11b). Kinetic energy has significantly higher values during the rainy season, which suggests that kinetic energy in the Caribbean is more related to eddy motion than to the main wind-generated currents. Higher values in both seasons occurred north of 14°N, along the track of the eddies, and also in the southwestern Caribbean. Preferred "pathways" of travel for the eddies were noticeable as localized kinetic energy maxima leading from the St. Lucia and Chibcha Channels.

The South American upwelling, which occurs along the Colombian and Venezuelan coasts in the central Caribbean, showed only relatively low variability and low amounts of eddy kinetic energy, possibly indicating that the upwelling is bound quite closely to the coast. Kinetic energy in the southwestern Caribbean showed high values throughout the year but especially during the rainy season when the eddies formed there.

5. Temporal Variability

Rms sea level, kinetic energy, and enstrophy averaged over the Venezuelan, Colombian, and Cayman Basins (see Figure 1b) were calculated for each half cycle. On the seasonal scale the variability of SLA through the observation period was related directly to the precipitation rate in each Caribbean basin and inversely to the wind speed, except during the Veranillo in July, which is a recognized (yet not well understood) wind pattern (Figures 12a, 12b, and 12c).

The kinetic energy was generally highest in the Colombian Basin (Figure 13), up to 0.42 $m^2 s^{-2}$, versus 0.38 $m^2 s^{-2}$ in the Cayman basin and 0.28 $m^2 s^{-2}$ in the Venezuelan Basin. The annual maximum occurred here in October of both years, and minimum occurred in May. Extreme values occurred earlier in the Venezuelan Basin, in August and December-January, respectively. In the Cayman Sea the annual cycle was less clear with several peaks and troughs, indicative of more localized effects, but again showed maxima in October 1992 and slightly earlier in June 1993, with a minimum in April. The general picture, however, was consistent with the advection of features westward from the Venezuelan to Colombian Basins and with less persistent communication to the Cayman Sea. The propagation of features occurred at a mean rate of ~15 km d^{-1}, assuming 10° of longitude between basin centers and 3-5 months lag. Kinetic energy levels were much lower all year in the Venezuelan Basin, with peak levels only about half the average value in the other two basins, indicating increased intensity of the eddy activity toward the west.

Overall, enstrophy showed similar behavior to the kinetic energy (Figure 14). Enstrophy in the Cayman Sea was highest during the last months of 1992 and then decreased until April, followed by another maximum in October, as was the case with the kinetic energy. The Colombian Basin exhibited roughly similar behavior, while lower levels of enstrophy in the Venezuelan Basin reflect less mesoscale activity in that area. The integral wave number modulus, calculated as the ratio of enstrophy and kinetic energy, gives an idea of the sizes of the eddies formed on each basin. In the Caribbean Sea the wave number modulus (Figure 15) showed the westward propagation of eddies since extreme values occurred first in the Venezuelan Basin followed by peaks in the Colombian Basin 1-2 months later and in the Cayman Basin in the next few weeks. The most pronounced effect occurred during September–October when the modulus reached high values. At this time the Venezuelan and Colombian Basins had opposite behavior, meaning that the eddy sizes increased in the Venezuelan Basin while the eddy activity in the Colombian Basin weakened or became shorter scale.

6. Conclusions

The results describe some important basic physical oceanography of the Caribbean Sea and raise fundamental dynamical issues of how these eddies form, propagate, and dissipate in the Caribbean. The analysis revealed the presence of significant eddies that traversed the Caribbean in a generally westward direction during the 14 month period of observation.

For the first time, results indicate that not just anticyclones but also cyclones traveled along the Caribbean Sea north of

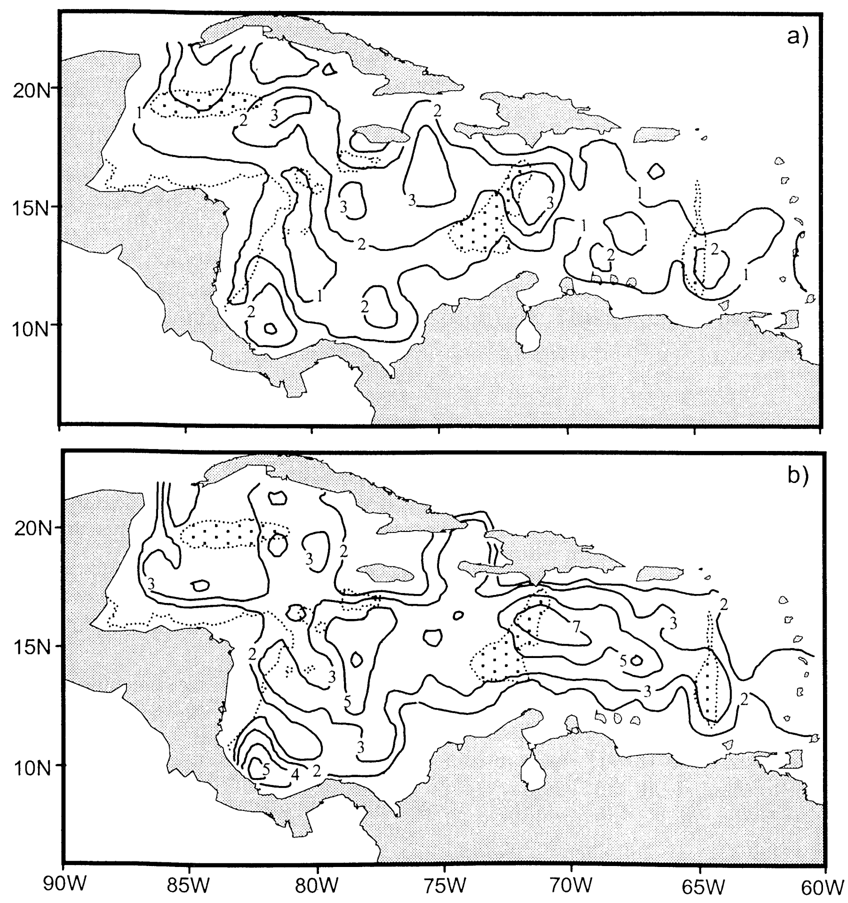

Figure 11. Kinetic energy (10 $m^2 s^{-2}$) in the Caribbean Sea during the (a) windy and (b) rainy seasons. Higher values are distributed zonally along higher latitudes, ~15°N, over the submarine ridges (shaded), especially south of Hispaniola, south of Jamaica, the Yucatan Channel, and the Gulf of Mosquitos.

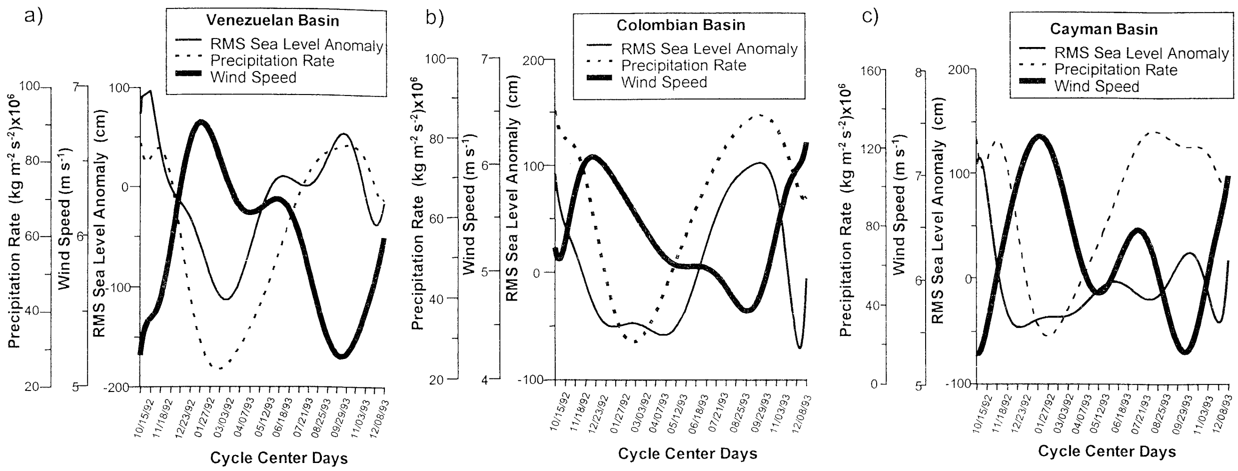

Figure 12. Comparison of wind speed and precipitation rates from *Climatic Diagnostics Center* [1998] monthly means and from ERS-1 over the (a) Venezuelan (b) Colombian, and (c) Cayman Basins. Anomalies in the sea level were greater when wind speed decreased and vice versa in all basins except during the midsummer drought [July] when the wind speed increased for 1 month. The SLA behaved similarly to the precipitation rate.

15°N. One eddy appear entered the Caribbean through Anegada Passage (Figure 4), and another entered through St. Lucia Channel. A third one formed or entered from north of Trinidad. As these traveled northwestward across the central Caribbean as far as 14°N, they increased in size. One eddy entered through the Windward Passage and traveled through the Cayman Sea exiting via the Yucatan Strait 6 months later. Few patterns of SLAs were conserved passing to the Cayman Sea from the Colombian Basin, but they did clearly in one case.

These eddies were seemingly advected by the mean flow in which they were embedded. They entered through the Antilles Arc or were formed from unstable meandering of the zonal flow through the Caribbean Sea. Advective speeds ranged from 20 cm s^{-1} for eddies traveling through the eastern Caribbean to a few centimeters per second when slowing down and intensifying in the central Caribbean. High rms sea level and eddy kinetic energy values in the center of the basin during July-October suggest that the enhancement of eddy motion in that zone has a direct relationship with the maximum curl of the north trade winds at the core of the low-level jet.

The typical timescale of synoptic eddies that traveled through the Caribbean was of ~100-130 days. Their size at maximum expansion in the center of the basin was typically up to ~500 km. This is significantly larger than the average size indicated by the integral wave numbers since the latter represent averages over basin-scale areas. Large eddies decay by topographic effects rather than other mechanisms. Almost all the eddies arrived at the Central American Rise and dissipated there; only a few passed through the Chibcha Channel to the Cayman Sea. The catastrophic interaction with topography as eddies collide against the shoals and banks of the area has great importance as a retention-expulsion mechanism for larvae and eggs [*Andrade et al.,* 1996].

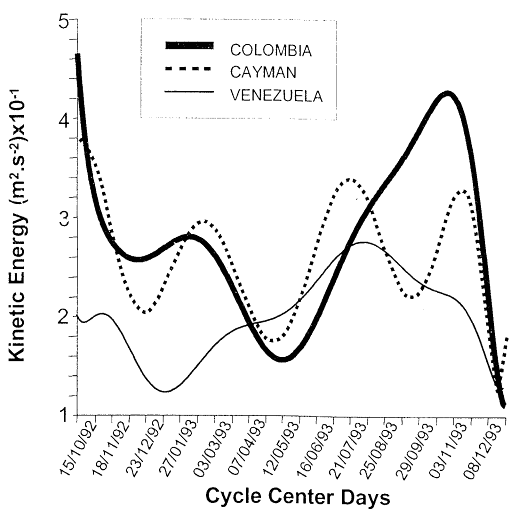

Figure 13. Kinetic energy in the Caribbean Sea calculated from ERS-1 SLAs from October 1992 to December 1993. The three basins behaved differently. The Colombian Basin was the most energetic. Maximum and minimum energy occurred earlier in the Venezuelan Basin, implying westward advection. The lack of a clear signal in the Cayman Basin may be related to the blocking of eddies by the Central American Rise.

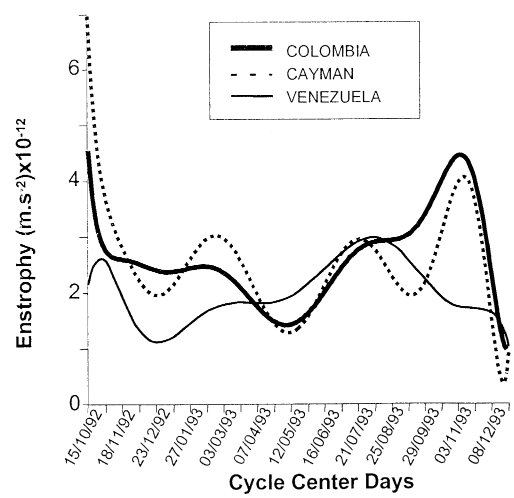

Figure 14. Integral enstrophy in the Caribbean Sea calculated from ERS-1 SLAs for October 1992 to December 1993. Peaks of enstrophy occurred in October-November. Irregular variation was seen otherwise.

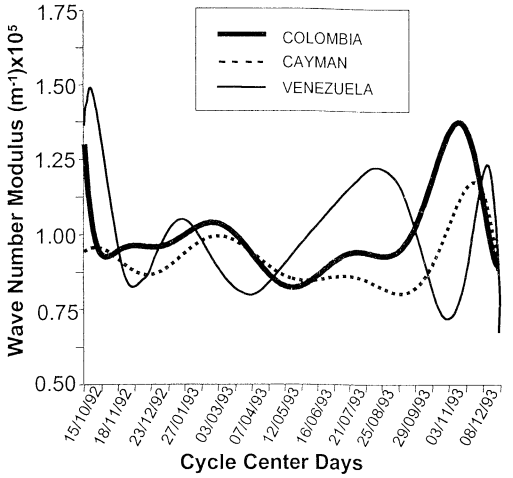

Figure 15. Integral wave number modulus for the three basins of the Caribbean calculated from ERS-1 SLAs. The Venezuelan Basin showed maximum variability, while the Cayman and Colombian Basins showed similar behavior with different amplitudes.

A cyclonic eddy formed in the southwestern Caribbean in August 1993, moved northeastward to merge with a cyclonic anomaly arriving from the east, expanded in diameter to ~700 km, and moved westward until dissipating 4 months later. The trajectory of this eddy broadly supported the idea of *Mooers and Maul* [1998] that the Panama-Colombia Gyre is a broad cyclonic circulation that advected eddies around the southwestern region, though no triad of eddies was found.

Eddies in the southwestern Caribbean had been noted earlier [e.g. *Wust,* 1963*; Gordon,* 1967*; Kinder*, 1983*; Nystuen and Andrade,* 1993] but never observed throughout their lifespan until this study. These eddies, which originated in the southwestern Caribbean Basin, are the only ones not advected from the eastern Caribbean or directly related to the instability and advection of the Caribbean Current. They remained largely in the southwestern Caribbean where they formed distinctive anomalies with average swirl speeds of ~40 cm s^{-1}.

The position of the ITCZ over the southwestern Caribbean during part of the year produces an intense precipitation maximum and curl maximum in the wind field. Probably, the eddies formed there are driven by the consequent meridional salinity gradient and by the direct action of both wind curl and stress. Direct observations taken by the Colombian National Hydrographic Service in the southwestern Caribbean during 1997 and 1998 will permit investigation of the subsurface structure of the cyclonic circulation, its variability, and its relation to the wind forcing.

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