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Caribbean Current and eddies as observed by surface drifters

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Abstract

Recent satellite-tracked surface drifter trajectories were analyzed to describe the mean currents and eddies in the Caribbean Sea. The structure of the Caribbean Current and its variability were determined from high-resolution $\frac{1}{2}$-degree maps of the mean velocity and eddy kinetic energy. Looping drifter trajectories were used to identify discrete cyclones and anticyclones, and their characteristics were described and related to the structure of the mean flow. The translation rate of eddies in different areas was found to be similar to the mean velocity of the local background flow fields, suggesting that the eddies were largely advected by the background flow. Ten energetic anticyclones translated westward at 13 cm/s in the Venezuela and Colombia Basins. These anticyclones tended to lie in two bands, centered near 15°N and 17°N, coinciding with two jets of the Caribbean Current. The northern weaker jet contains water primarily from the North Atlantic; the southern stronger jet contains water from the tropical and South Atlantic. The anticyclones are thought to have formed in the eastern Caribbean from the anticyclonic vorticity derived from North Brazil Current rings. The ring vorticity enters the eastern Caribbean through island passages and is probably amplified by the anticyclonic shear on the northern side of the jets. Southwest of Cuba a cyclone–anticyclone pair was observed to translate slowly (~2 cm/s) westward into the Yucatan Current. The cyclone was tracked for 10.5 months with four drifters, making it the longest tracked of the Caribbean eddies.
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1. Introduction

Recently, a large number of satellite-tracked, drogued, drifting buoys measured trajectories in the Caribbean Sea (Fig. 1). Many drifters were launched in the Caribbean during 1998–2000 as part of the "Year of the Ocean-1999" study (Wilson and Leaman, 2000) (Fig. 2). Other drifters were launched east of the Caribbean in other experiments including the North Brazil Current (NBC) rings experiment (Fratantoni and Richardson, 2004); these drifters passed through the Antilles Islands passages adding trajectories in the Caribbean. Taken together, these trajectories provide a unique data set that reveals previously unknown details of the circulation and eddies in the different parts of the Caribbean. The intent of

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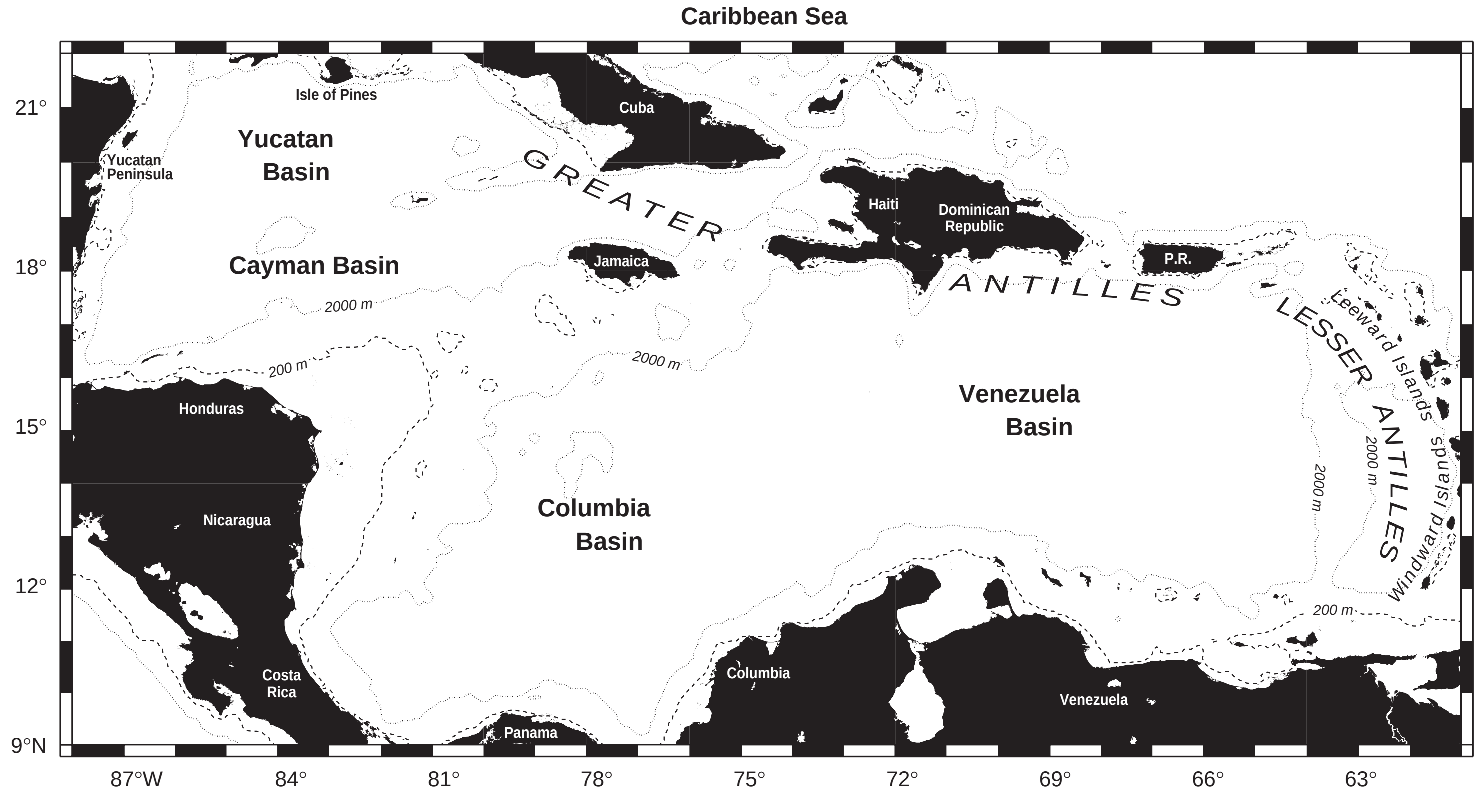

Fig. 1. Location diagram showing the major Caribbean basins, the surrounding countries and islands, and the 200 m (dashed) and 2000 m (dotted) depth contours. The relatively shallow Jamaica Ridge extends from the Honduras shelf to Hispaniola and separates the Yucatan and Cayman Basins of the western Caribbean from the Venezuela and Colombia Basins of the eastern Caribbean.

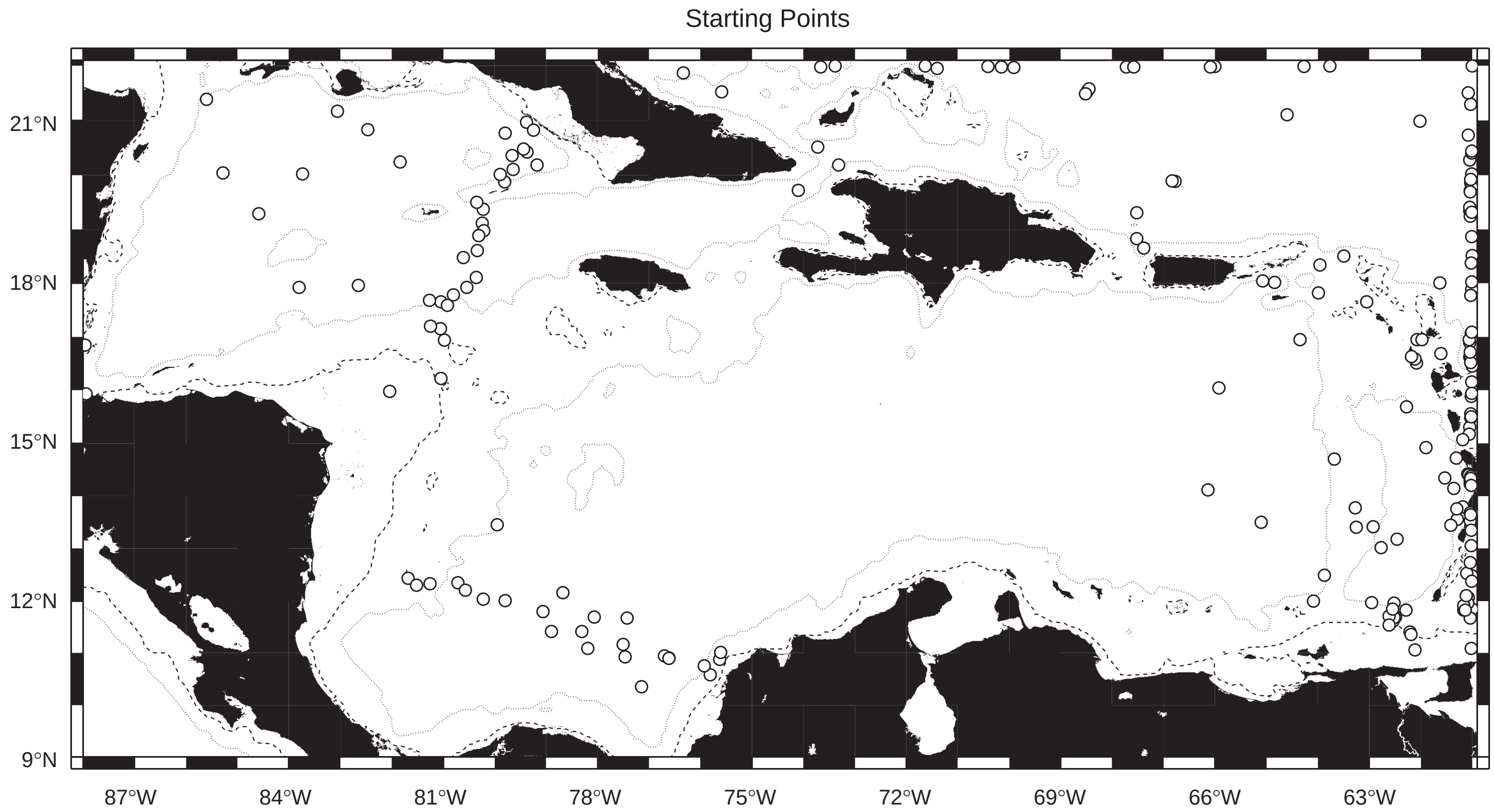

Fig. 2. Launch or start locations of 212 drifters used in this study. One hundred and eighteen drifters were launched in the Caribbean including 40 in the western Caribbean, 24 in the southern Colombia Basin, and 54 in the eastern Caribbean. Ninety-four others were launched outside the Caribbean including 66 that entered the box from the east across 61°W and 13 that entered from the north across 22°N.

this paper is to analyze these data with the goal of learning more about the characteristics of Caribbean eddies in general and specifically about the energetic anticyclones in the eastern Caribbean that might have been generated by NBC rings. Satellite altimetry studies suggest that some NBC rings can pass coherently through the Antilles passages into the Caribbean (Goni and Johns, 2003). The motivation for the present study is to see whether the drifter data could provide evidence that Caribbean anticyclones are generated by NBC rings.

Although the mean velocity field and velocity variance have been mapped recently for the Caribbean using surface drifters (Wilson and Leaman, 2000; Fratantoni, 2001; Centurioni and Niiler, 2003), and trajectories of drifters looping in eddies have been shown and briefly described (Centurioni and Niiler, 2003), these data have not yet been used to thoroughly describe discrete eddies in the Caribbean. The new drifter trajectories provide an important new Lagrangian picture of Caribbean eddies, but the eddies were discussed only briefly in the short paper by Centurioni and Niiler. They used a high-resolution ($\sim\frac{1}{2}$ degree) mapping grid to show detailed views of velocity vectors in subregions of the Caribbean, but no mean velocity map of the whole Caribbean was included. This present paper builds on these earlier studies by first using drifter trajectories to map the circulation and eddy kinetic energy (EKE) of the whole Caribbean at high resolution ($\frac{1}{2}$ degree) and then to systematically identify and describe several different kinds of discrete eddies in order to show where they occur in relationship to the mean current field and to estimate their translation rates, swirl velocities, and overall sizes.

Eddies in the Caribbean are important for several reasons. First, the various source waters of the Caribbean Current coming from the North Atlantic, South Atlantic, and nearby Amazon and Orinoco Rivers are advected and stirred by the eddies' swirl velocity, which can be much larger than the velocity of the mean field. Numerous large and energetic eddies translating westward through the Caribbean blend and mix the source waters together. Second, eddies interact with the boundaries and often sweep near-shore water away from the coast into deeper regions and vice versa. This has important implications for the dispersal of pollutants and fish larvae, e.g. Third, eddies appear to have some preferred pathways through the Caribbean that cause bands of higher and lower (rectified) mean westward velocity coinciding with westward jets in the Caribbean Current and which suggests that eddy-mean flow interactions could be important. Fourth, eddy forcing of the circulation of deeper layers in the Caribbean could be significant if the energetic eddies extend deeply into the water column like some NBC rings. Fifth, Caribbean eddies can be advected into the Yucatan Current and influence the path of the Loop Current in the Gulf of Mexico and the formation of Loop Current rings there.

2. Background

The Caribbean Current is the major route by which South Atlantic water flows into the Florida Current and Gulf Stream and is therefore an important conduit of the upper part of the northward-flowing meridional overturning circulation (MOC) (Schmitz and Richardson, 1991; Schmitz and McCartney, 1993). The Caribbean has two nearly equal sources of inflow water (see Johns et al., 2002). North of (roughly) Martinique near 15°N Caribbean inflow is primarily Gulf Stream water returning southwestward in the North Equatorial Current. This water passes through the Leeward Islands of the Lesser Antilles, through the Windward Passage between Cuba and Hispaniola, and through the Mona Passage between Hispaniola and Puerto Rico.

South of 15°N Caribbean inflow is primarily of tropical and South Atlantic origin. South Atlantic water crosses the equator in the NBC and flows northwestward along the continental margin of South America in the form of a coastal current (Candela et al., 1992), in NBC rings (Johns et al., 1990; Didden and Schott, 1993; Richardson et al., 1994; Fratantoni et al., 1995), plus some in Ekman transport in the ocean interior (Mayer and Weisberg, 1993). The NBC retroflects near 6°N and feeds into the eastward-flowing North

Equatorial Countercurrent. Periodically, roughly 8–9 times per year, large 400-km diameter NBC rings pinch off from the retroflection and translate northwestward toward the Caribbean at around 15 cm/s (Johns et al., 2003; Garzoli et al., 2003; Goni and Johns, 2003; Fratantoni and Richardson, 2004). Most rings translate northward just east of the Antilles to around 14–18°N where the rings stall and decay (Fratantoni and Richardson, 2004; Goni and Johns, 2003). Some rings disappear after they collide with the continental margin and islands south of 14°N. Most South Atlantic water carried by rings enters the Caribbean, episodically, through island passages south of 18°N (Fratantoni and Richardson, 2004), although some near-surface water in the rings passes northward around the islands.

Of the 28 Sv (1 Sv = $10^6\,m^3/s$) of total transport through the Caribbean, 10 Sv enter the Caribbean through the southern or Windward Islands passages, 8 Sv enter through the northern or Leeward Islands passages, and 10 Sv enter through the Greater Antilles Islands passages (Johns et al., 2002). Roughly, half of the Caribbean transport is derived from the South Atlantic and around half (or more) of the South Atlantic water is transported by NBC rings (Johns et al., 2002, 2003).

Maps of historical shipdrift velocity and EKE show a swift flow of water and a band of high EKE extending from the equator along the northeastern coast of South America through the Caribbean into the Gulf Stream (Wüst, 1964; Wyrtki et al., 1976). This pattern has recently been confirmed and refined using surface drifters and satellite altimetry (see Fratantoni, 2001). The recent drifter, current meter, and altimetry data show that energetic NBC rings translating northward along the northern coast of South America up to the Caribbean are primarily responsible for the band of high EKE, and to a large extent responsible for the significant (rectified) mean velocity field of the Guiana Current (Richardson et al., 1994). These rings appear to be responsible, either directly or indirectly, for the high EKE in the Caribbean (Fratantoni et al., 2000; Johns et al., 2002).

Model simulations suggest that NBC rings and the high EKE band extending through the Caribbean to the Gulf Stream are a consequence of the superposition of a realistic MOC and a realistic wind-driven circulation. Without the MOC there were no NBC rings and much lower EKE. Thus, model simulations provide evidence of a link between the MOC, the formation of NBC rings, the variability of flow into the Caribbean, and the eddy field there (Fratantoni et al., 2000; Johns et al., 2002; Barnier et al., 2001). The eddy field in the Caribbean thus could be caused by rings (or their remnants) translating through the island passages into the Caribbean where the ring vorticity acts as a perturbation for instabilities of the Caribbean Current (see Murphy et al., 1999).

NBC rings have been tracked with surface drifters that were trapped and looped in the rings' swirl velocity (Richardson et al., 1994; Fratantoni and Richardson, 2004), by satellite altimetry that measured the positive sea-level anomalies in the central regions of rings (Didden and Schott, 1993; Goni and Johns, 2001, 2003), and by ocean-color images that detected the chlorophyll-rich water from the Amazon advected around the periphery of rings (Johns et al., 1990; Fratantoni and Glickson, 2002). Some rings tracked by altimetry appeared to coherently enter the Caribbean, but their signal became weaker there, and they could not be tracked for long (Goni and Johns, 2003). The wide spacing between satellite altimeter lines makes it difficult to see details of the ring anomalies as they enter the Caribbean. Most drifters that had been in rings near the Antilles passed through the island passages into the Caribbean (or grounded on the islands or were retrieved at sea and taken ashore), implying that most ring water enters the Caribbean. However, there has been no real evidence from drifters that rings pass coherently through island passages.

Satellite altimetry has been used to measure the anomalous sea-level signal of some eddies in the Caribbean (Nystuen and Andrade, 1993; Schott and Molinari, 1996; Carton and Chao, 1999; Pauluhn and Chao, 1999; Andrade and Barton, 2000; Astor et al., 2003). Several large eddies were identified that translated westward in the Caribbean at speeds of 15 cm/s with some evidence of the eddy anomalies increasing as they translated (Carton and Chao, 1999). Both anticyclones and cyclones were observed, but anticyclones appear to be most prevalent. A difficulty in using altimetry to observe eddies is the necessity of estimating the seasonally varying sea level of the Caribbean, given its complicated structure, so that sea-level anomalies can be accurately estimated and tracked. Despite these difficulties, some altimeter observations suggest a possible connection between NBC rings and Caribbean anticyclones (Carton and Chao, 1999). Satellite ocean-color images also have been used to identify a Caribbean eddy, which was confirmed by shipboard measurements (Corredor et al., 2004).

Some of the first direct velocity observations of eddies in the Caribbean were made by drifters deployed in 1975–1976 when satellite tracking first became available (Molinari et al., 1980, 1981; Heburn et al., 1982; Kinder, 1983; Kinder et al., 1985). The drifters meandered through the Caribbean and occasionally looped in a few anticyclones illustrating time-dependent fluctuations. Because the early trajectories were relatively sparse, it was difficult to infer much about eddy characteristics. The drifter observations were grouped to map the mean velocity (and variance) in 2-degree bins, creating one of the first directly measured velocity fields of the Caribbean (Molinari et al., 1980). Other early maps of directly measured currents in the Caribbean were based on historical ship drifts (see Wüst, 1964). It is instructive to see the changes between the broad current in these early maps and the details of smaller-scale features being resolved in the more recent higher-resolution ones as shown by Centurioni and Niiler (2003) and in this present paper.

More complete descriptions of the Caribbean circulation and aspects of its variability have been given by Wüst (1964), Schott and Molinari (1996), Mooers and Maul (1998), Centurioni and Niiler (2003), and Gyory, Mariano and Ryan at the website: http://oceancurrents.rsmas.miami.edu.

3. Methods

During the last 8 years (1996–2003) over 73,000 6-hourly positions and velocities were measured with 212 drifting buoys in the Caribbean Sea (Fig. 3). The drifting buoy data were acquired from the Global Drifting Buoy Data Assembly Center at the National Oceanic and Atmospheric Administration Atlantic Oceanographic and Meteorological Laboratory in Miami Florida. The majority of the drifters were similar to the WOCE–TOGA Lagrangian drifter described by Sybrandy and Niiler (1991). Drogues were attached below the surface float centered at a depth of 15 m. Positions of a few drifters were based on satellite fixes obtained every 3 days (to reduce costs), which provided some slightly odd-looking interpolated trajectories compared to the usual ones based on several satellite fixes per day. Since the looping period of the eddies was usually much greater than 3 days, these interpolated data were used where appropriate. Earlier trajectories from 1975 to 1976 were not included because of different drogues, drogue depths, problems with drogue retention and drifter slip due to wind and wave forces on the surface floats.

Box averages of velocity and EKE were generated by grouping all available 6-hourly drifter velocities into boxes. Mean velocity was calculated as the sum of all u velocity components in a box (in the x direction) divided by the number of observations, similarly for v velocity in the y direction. EKE was calculated by averaging the u and v velocity variances (variances about the mean velocities) in each box. Standard error of mean velocity was estimated using $\sqrt{2st/N}$, where s is the variance of velocity about the mean velocity, N is the number of 6-hourly velocity observations divided by 4, and t is the integral time scale of the Lagrangian autocorrelation function, which was estimated to be 2 days. In practice, the number of degrees of freedom, N/t, was estimated by summing the number of 2-day intervals for which each drifter was within a box.

Rossby number (Ro) was estimated for some eddies by $Ro = \zeta/f$, where $\zeta = 2\omega$ is the relative vorticity of an eddy (assuming solid body rotation), ω is the angular velocity of the eddy, and f is the Coriolis parameter, $f = 2\Omega \sin\theta$. If a drifter was located outside the (approximately) solid body rotation core region of an eddy, then the calculated Rossby number could be an over estimate. The relative vorticity of an eddy can be

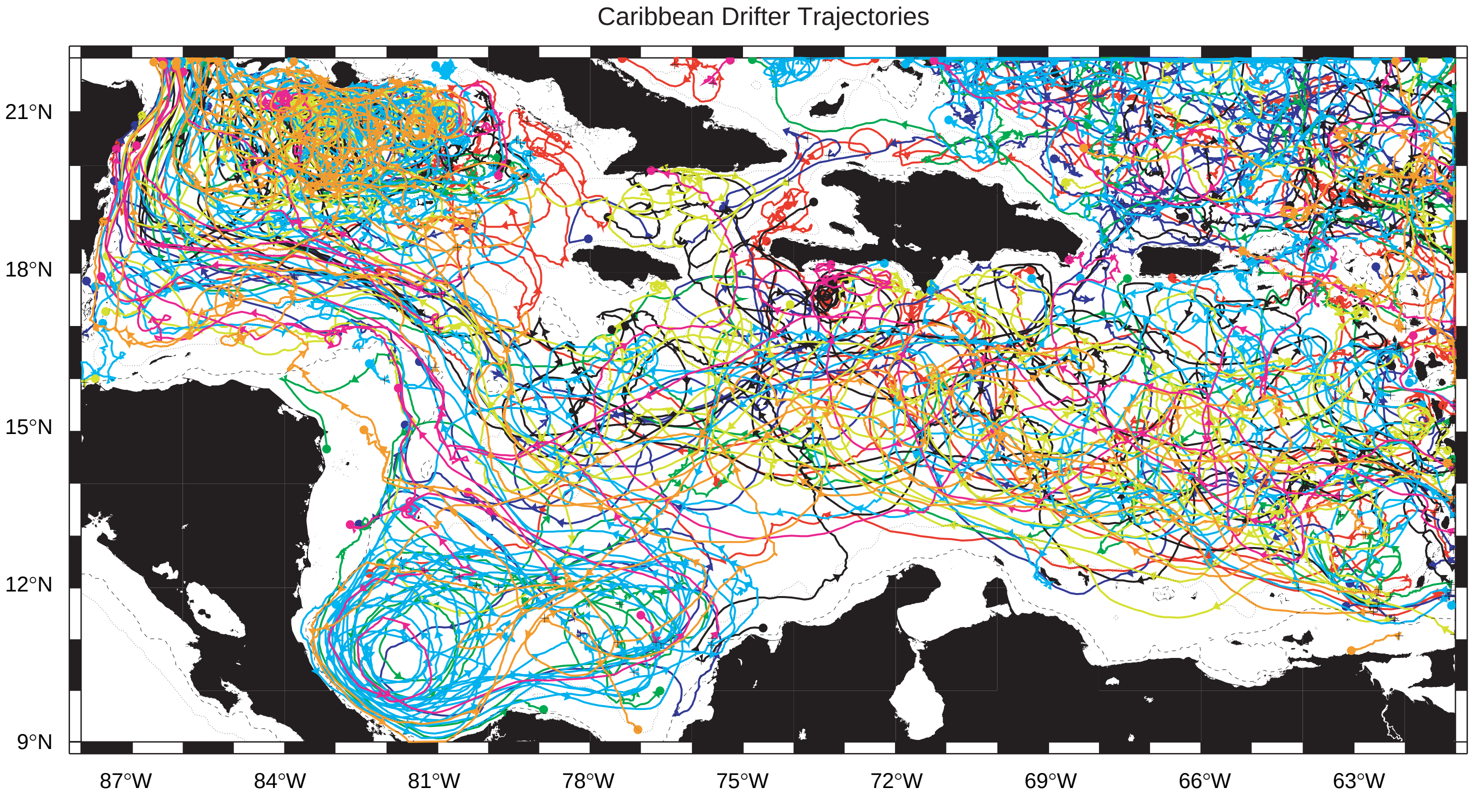

Fig. 3. Summary of 212 surface drifter trajectories in and near the Caribbean and over 50 drifter years of data from the years 1986–2003. Most observations come from the years 1998–2000. Arrowheads are spaced at 10 days. Trajectories clearly show the cyclonic Panama–Colombia Gyre centered near 11°N 81°W. Many drifters looped for long times in eddies in the eastern Caribbean and in the western Caribbean southwest of Cuba.

expressed in terms of its period of rotation (T in days) as $f/(T \sin\theta)$. T was estimated from the looping drifters. $\sin\theta$ for the mid-part of the eastern Caribbean (14–15°N) is around 0.25.

4. Drifter data

4.1. Trajectories

A summary of drifter trajectories (Fig. 3) illustrates some characteristics of currents and eddies. In general, the Caribbean is filled with a complex tangle of trajectories indicating time-dependent fluctuations, which are primarily due to eddy motions. In particular, the region southwest of Cuba appears to be densely packed with convoluted trajectories, which give little indication of any mean flow. In contrast to this are two regions where trajectories lie roughly parallel to each other, indicating that mean flow dominates over the eddies. One is in the southern Colombia Basin where numerous drifters circled the counterclockwise Panama–Colombia Gyre. The second is in the western Caribbean where drifters went westward just north of Honduras and then turned and went northward in the Yucatan Current, which exits the Caribbean between Yucatan and Cuba.

Expanded plots of the Panama–Colombia Gyre are shown in Fig. 4. Almost all drifters that circled the gyre were launched there. One circled the gyre 11 times during 13 months (Fig. 4B). Thirteen of these drifters eventually left the gyre by drifting northwestward. Only one drifter from the eastern Caribbean was entrained into the gyre circulation. The gradual flushing out of the gyre of drifters launched there and the lack of others entering the gyre from the east is attributable to a mean northwestward near-surface flow driven by the mean easterly trade winds. Many other drifters grounded on the east-facing coast of Nicaragua due to onshore winds there.

Several drifters looped in the nearly circular western part of the gyre centered near 11.0°N 81.5°W and bounded by 9–13°N 80–84°W. The southwestern part of this gyre is tightly confined to the coast of Costa Rica, where the main current appears to be only 50-km wide. Numerous other loops in the gyre extended eastward to around 75°W suggesting that the western part is embedded in a much larger gyre. The eastern part contains significant time variability partially due to two westward translating cyclonic eddies located there.

Mooers and Maul (1998) have reported that the Panama–Colombia Gyre "consists of an intense cyclone that together with an adjoining anticyclone and cyclone is embedded in a larger but weaker cyclonic gyre". The cyclonic eddies observed by drifters could be interpreted as the "adjoining cyclone", but there are no obvious anticyclonic loops in the vicinity of the gyre and no confirmation of the "adjoining anticyclone".

Monthly maps of trajectories in the gyre, not shown, do not reveal an obvious seasonal variation, aside from the two cyclones, although the data are rather sparse at this resolution. Thus, the cyclonic gyre was quasi-permanent during the 19-month period from June 1998 to December 1999 when the data are available. Maps of historical shipdrift velocities, summarized by Rennell (1832) and Wüst (1964), suggest the gyre existed over much longer time scales (~200 years).

Ten drifters transited through the whole Caribbean illustrating the main pathways of flow through the Caribbean Sea (Fig. 5). Four other drifters almost completed the trip but grounded on the coast of the Yucatan Peninsula, due in part to the mean trade winds blowing onshore there. Most of the drifters looped in eddies including some large ones, ~250 km in diameter, in the Venezuela Basin. On average the 10 drifters spent 6.2 months in passing through the Caribbean, with a range of 3.4–8.0 months.

The envelope of these 10 drifter trajectories gradually narrows to 100 km in the west where drifters were funneled through gaps in the Jamaica Ridge. West of the ridge the envelope widens somewhat before narrowing again as drifters were funneled into the 150-km wide Yucatan Channel. Five of the drifters exiting in the Yucatan Current returned southward again on the east side of the channel indicating inflow to the Caribbean there.

(A)

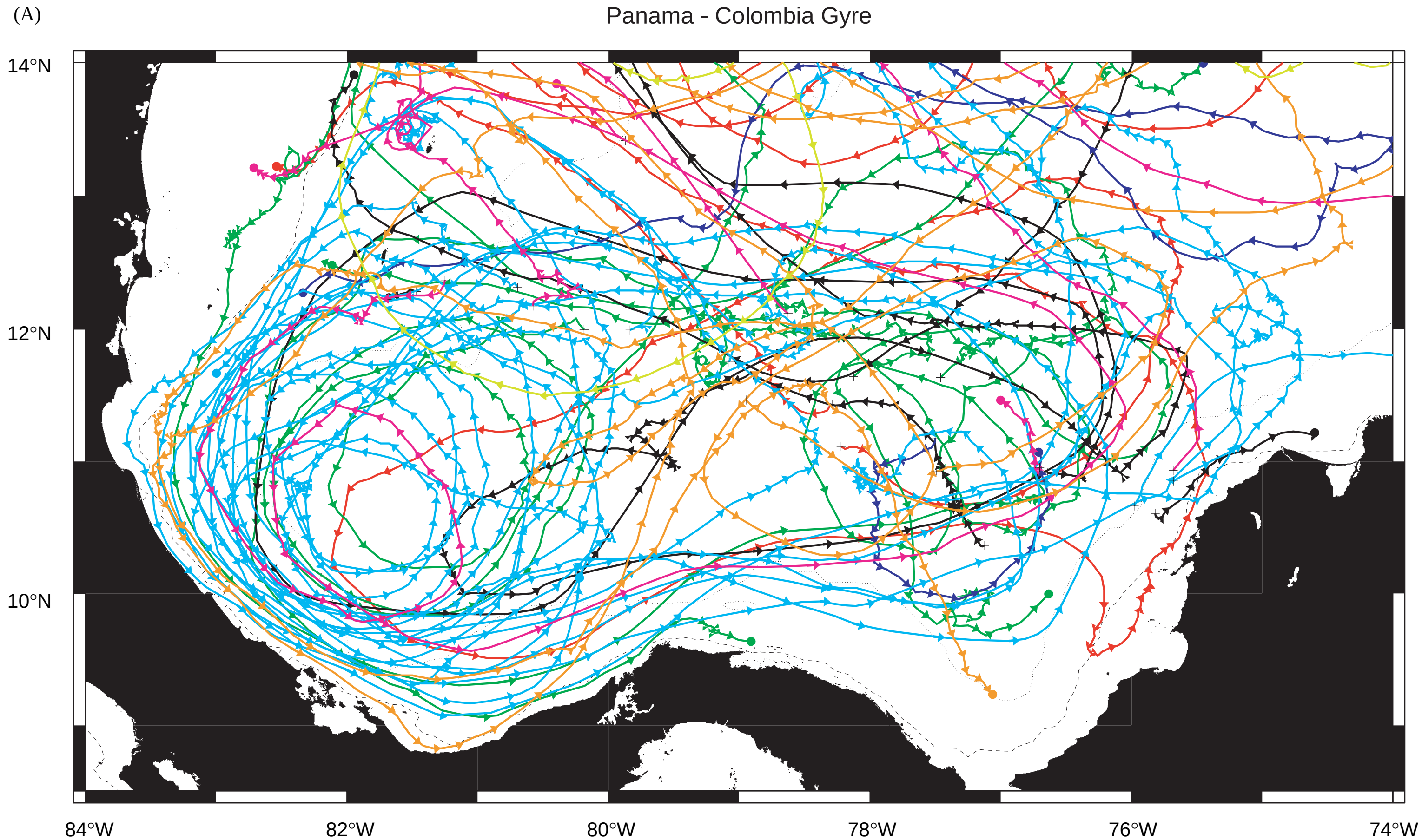

Fig. 4. (A). Drifter trajectories in the Panama–Colombia Gyre region. A major source of the variability in the eastern half of the gyre is two 200-km diameter cyclones that drifted westward at 3–5 cm/s near 11°N. These cyclones, which are difficult to see here, will be shown later without background drifters (Fig. 11). Arrowheads are spaced at 1-day intervals. (B) Trajectory of a drifter launched in the Panama–Colombia Gyre near 10.8°N 75.6°W that circled in the gyre 11 times during June 1998–July 1999. This is the longest-lasting drifter in the gyre. Arrowheads are spaced at 1-day intervals.

(B)

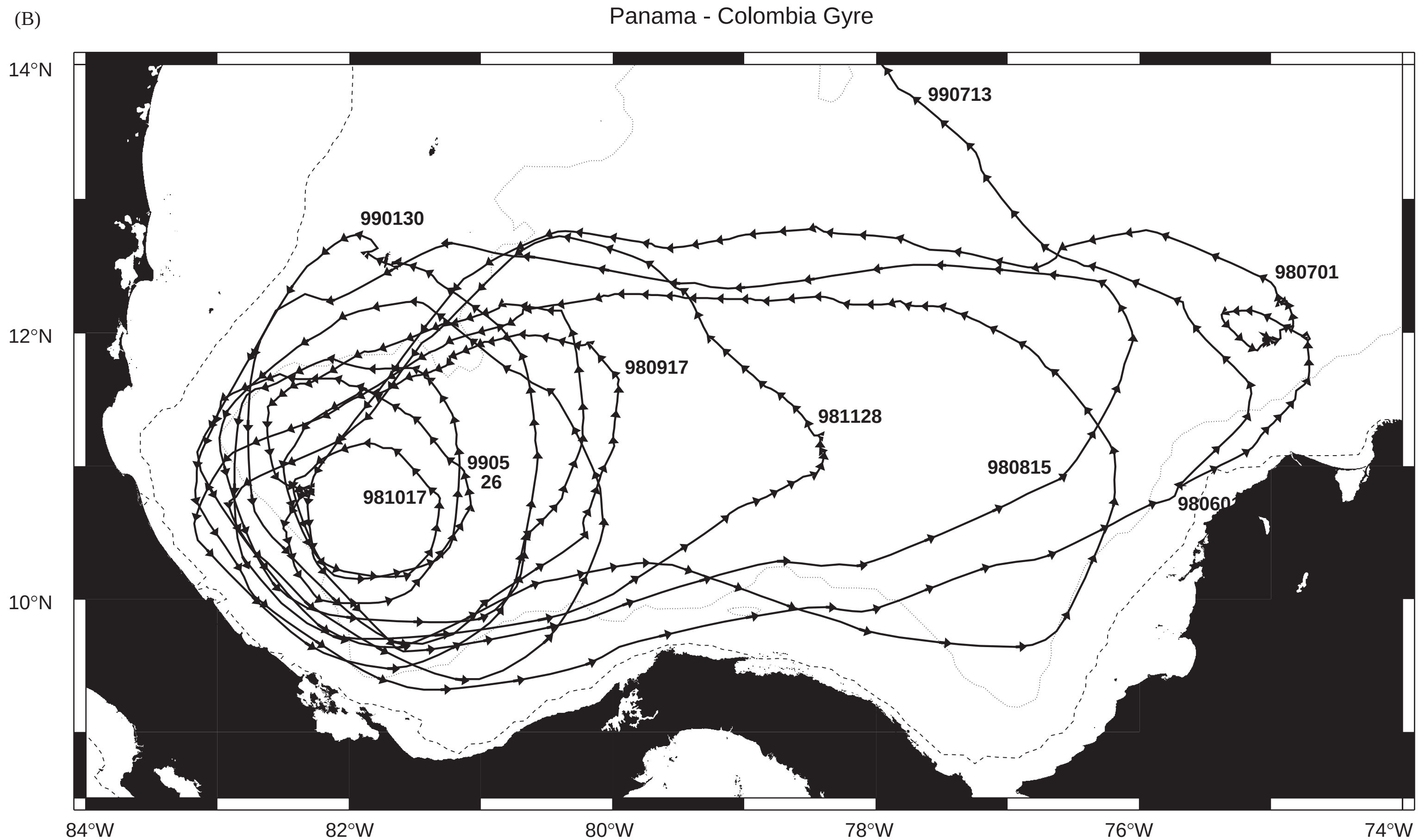

Fig. 4. (*Continued*)

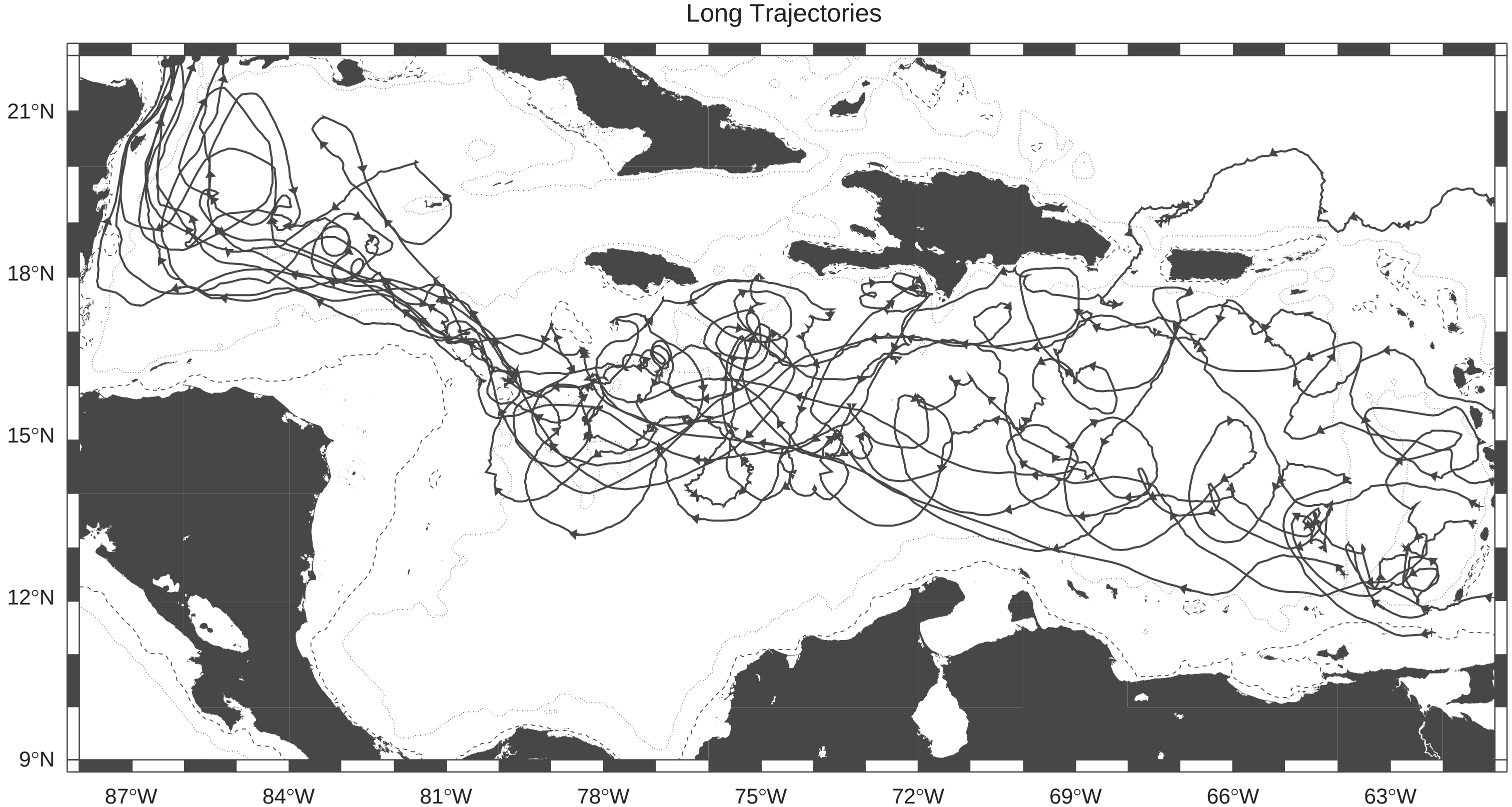

Fig. 5. Trajectories of 10 drifters that drifted through the Caribbean and exited through the Yucatan Straits. Three drifters entered the Caribbean through island passages; seven others were launched in the eastern Caribbean. Some looping trajectories reveal the presence of eddies, primarily anticyclones, in the eastern Caribbean. Arrowheads are spaced at 10 days.

4.2. Speeds

A plot of drifter speeds along trajectories (Fig. 6) reveals regions where high and low speeds dominate. Although highest speeds (~100 cm/s) are scattered throughout the Caribbean, they appear to be concentrated in the Yucatan Current and along the southern boundary especially noticeable in the eastward-flowing southern part of the Panama–Colombia Gyre and in the Caribbean Current along the boundary of Venezuela and Colombia. Low speeds are seen throughout the Caribbean but are dominant in the northeastern region inside and outside the Caribbean and also just south of Cuba.

4.3. Mean velocity vectors

The pattern of trajectories and their speeds in different parts of the Caribbean look very different, suggesting different current regimes including different mean flows and different kinds and numbers of eddies. To explore these geographical variations more quantitatively bin-averaged mean velocity vectors were mapped in Fig. 7 and velocity variances about the mean, or EKE, in Fig. 8.

The swiftest part of the Caribbean Current, >25 cm/s, shown by red arrows in Fig. 7, flows westward along the southern boundary of the Venezuela Basin near 12–15°N with mean speeds up to 80 cm/s. It continues through the mid-part of the Colombia Basin near 14–16°N, northwestward through gaps in the Jamaica Ridge near 81°W, westward north of Honduras between 18°N and 19°N, and northward along Yucatan near 86–87°W where speeds reach 120 cm/s. In the Colombia Basin, the Caribbean Current vectors merge with those in the westward-flowing northern limb of the Panama–Colombia Gyre, which extends from 9°N to roughly 14°N. In the southern part of the gyre mean speeds are around 75 cm/s. The swift part of the Caribbean Current can be traced back to the southeastern corner of the Caribbean where tropical and South Atlantic water enters the Caribbean from the NBC and from rings that collide with the continental margin near Tobago and with the southern islands in that region. Two fast flows (>25 cm/s) appear to enter the southeastern Caribbean passages near 12°N and 14°N (61°W) and merge into the main Caribbean Current by 66°W near 13°N.

A second somewhat slower (25–30 cm/s) and narrower band of westward flow, which lies in the northern Caribbean just south of Hispaniola (16–17°N), merges with the main southern part of the Caribbean Current near 75°W. This northern band of current appears to extend eastward to the islands near 17°N where water enters from the North Equatorial Current and from NBC rings that stall and decay near 15–18°N. The two bands of westward flow were identified by Centurioni and Niiler (2003) and also appear in the lower-resolution velocity map shown by Fratantoni (2001).

Elsewhere the mean velocity is generally slower (<25 cm/s) to the west although the mean flow just south of Cuba is particularly weak ~2 cm/s and difficult to see. A few red arrows are located near the Windward Passage near 20°N 74°W. The mean velocity in this region (19.0–20.5°N 73.5–75.0°W) is 13 ± 5 cm/s southwestward, indicating significant inflow. Northeast of the Caribbean in the area of the Antilles Current is ~6 cm/s flow to the northwest.

4.4. Eddy kinetic energy

High values of EKE (>800 cm^2/s^2) shown by yellow–red colors are prevalent in the central Venezuela and Colombia Basins and in a few areas of the Yucatan and Cayman Basins (Fig. 8). Coinciding with the high EKE values in the central Caribbean are numerous energetic anticyclones discussed below. Low EKE values shown by blue colors (~200 cm^2/s^2) dominate the region northeast of the Caribbean, the region just south of Cuba and in the western Panama–Colombia Gyre. The low EKE values in the gyre are located near some of the largest mean vectors, indicating the low temporal variability of the gyre structure in the west. Low values of EKE are also located in the swift part of the Caribbean Current north of Honduras 18–19°N, indicating low variability of this part of the current.

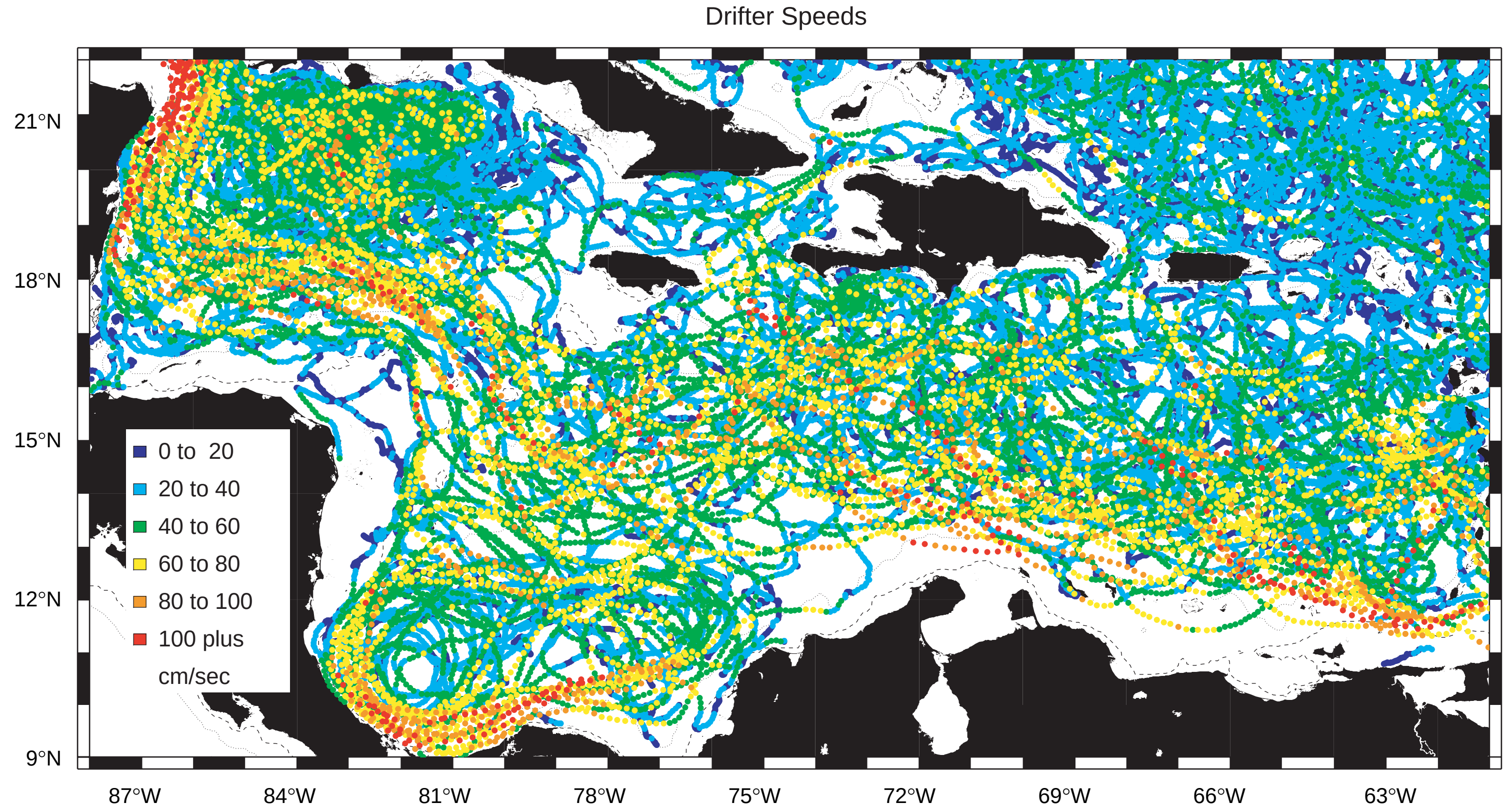

Fig. 6. Drifter locations color-coded to indicate speed. Over 73,000 individual 6-hourly velocity measurements are shown as colored dots. Fastest speeds shown in red are plotted over slowest speeds shown in blue. Fastest speeds >100 cm/s are clustered along the southern boundary of the Venezuela and Colombia Basins and along the western boundary off the Yucatan Peninsula.

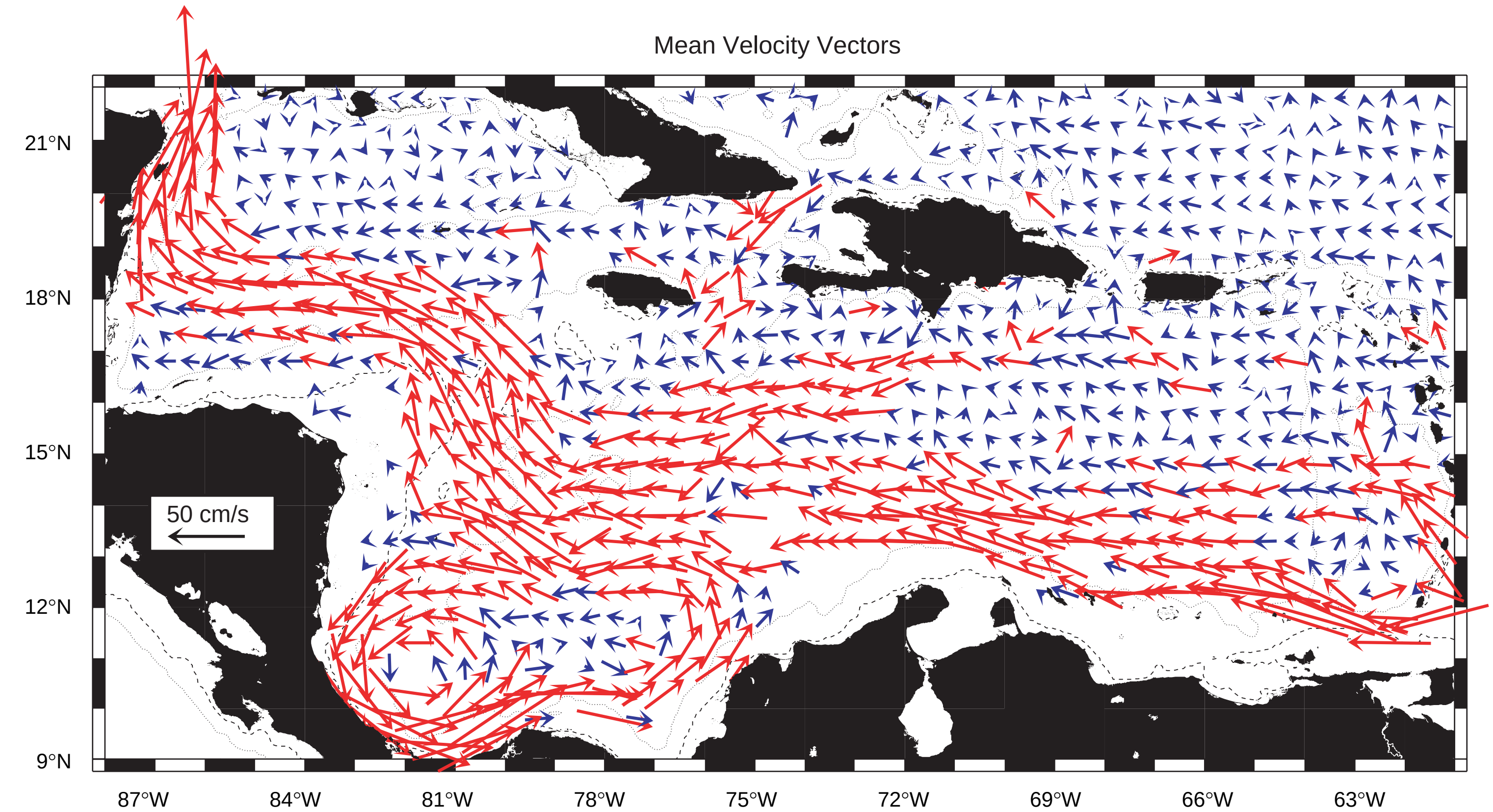

Fig. 7. Mean velocity vectors calculated by grouping 6-hourly velocity values into $\frac{1}{2}$-degree by $\frac{1}{2}$-degree bins. Vectors are shown for all bins that contained more than three degrees of freedom (see text). The swift Caribbean Current is shown by red vectors (>25 cm/s) to flow westward through the southern part of the Caribbean except north of the Panama–Colombia Gyre located in the southern Colombia Basin.

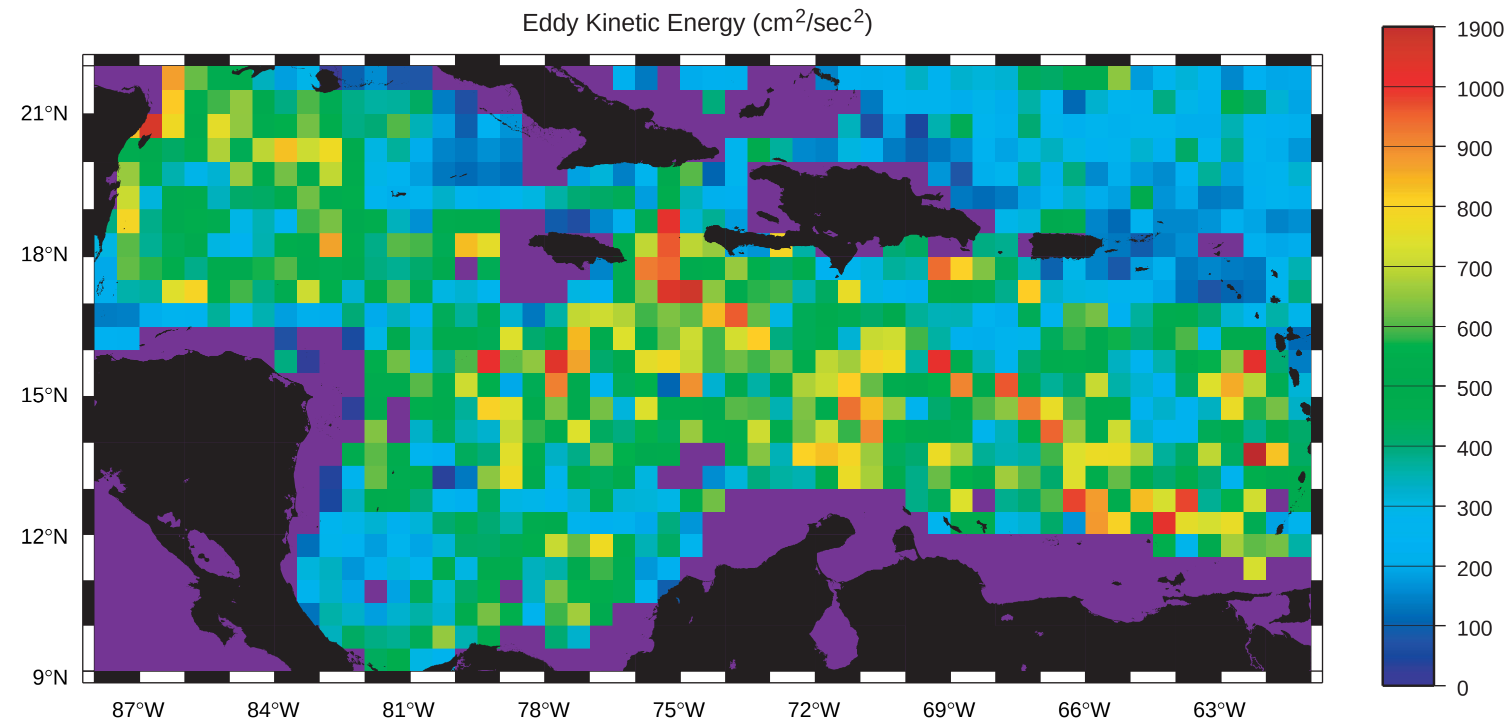

Fig. 8. EKE (cm^2/s^2) estimated from drifter velocity variances in $\frac{1}{2}$-degree by $\frac{1}{2}$-degree bins. EKE is large throughout the eastern Caribbean except in the Panama–Colombia Gyre and in the northeastern region north of the Caribbean where EKE is low.

5. Caribbean eddies

In order to investigate Caribbean eddies each drifter trajectory was inspected for loops and cusps, which reveal the characteristic motion of a particle in an eddy consisting of a swirl velocity, around the eddy center plus its translation. Time series of velocity were studied to estimate when a drifter entered and exited an eddy. Portions of trajectories that contained two or more loops in the same direction (loopers) were interpreted to have been in the swirl velocity of a discrete eddy. The term ''eddy'' is used to refer to both clockwise rotating anticyclones and counterclockwise rotating cyclones. Loopers were used to obtain information about eddy diameter, rotation period, swirl velocity, translation velocity, and eddy trajectories. Since the period of rotation and swirl velocity vary with radius, these characteristics estimated from drifters are representative of the radius sampled by the drifters. This should be kept in mind when comparing characteristics of different eddies. The primary emphasis here is on the numerous energetic anticyclones in the Venezuela and Colombia Basins, but eddies in other areas of the Caribbean are also discussed.

5.1. Examples of anticyclones

A good example of a large and energetic anticyclone in the central Caribbean is shown by trajectories of five different drifters during a 7-month period (Fig. 9). Trajectories of two loopers are shown plus five shorter pieces of trajectories (not official loopers) considered to have been in the swirl velocity of this anticyclone for various amounts of time. The anticyclone translated from near the southeastern corner of the Caribbean, near 64°W, 1700 km westward up to the Jamaica Ridge near 80°W. The longest looper consisting of 8.5 loops over 4 months at an average diameter of 167 km (Table 1) went westward at 11 cm/s. The envelope of the looping trajectories suggests the eddy diameter was nearly 300 km or around half the north–south extent of the Caribbean there. The overall diameter of the anticyclone was probably larger than this. Fastest swirl velocities were around 70 cm/s at a diameter of 200 km. The EKE of the looper with largest loops was around 1500 cm^2/s^2, suggesting that this anticyclone and others are major contributors to the high EKE in the eastern Caribbean.

Another example of an anticyclone in the central Caribbean is shown in Fig. 10. Anticyclone 5 was tracked with two drifters (one looper) for 4 months as it translated at 14 cm/s from the eastern Caribbean near 62°W westward up to a location near the Jamaica Ridge near 74°W. Swirl speeds were around 30 cm/s at a diameter of 100 km. The combined trajectories suggest an overall diameter of around 200 km. The typical maximum swirl speed of the eastern Caribbean anticyclones is around 60 cm/s, somewhat faster than this second example.

5.2. Loopers

The drifter trajectories in these two anticyclones are representative examples of the numerous anticyclones that dominate the Venezuela and Colombia Basins. A summary of all loopers in the Caribbean is shown in Fig. 11, and the inferred paths of the eddy centers in Fig. 12, subdivided by color into red anticyclones and blue cyclones. Overall 19% of the total drifter data in the large box (Fig. 3) are loopers, and these are almost evenly split into 28 cyclonic loopers and 29 anticyclonic loopers. These loopers were judged to have been in 49 different eddies, including 25 cyclones and 24 anticyclones.

The mean westward velocity of all drifters in the large box (Fig. 3) is 9.1 ± 0.4 cm/s (Table 2). Loopers translated at an average 5.2 ± 0.9 cm/s, anticyclonic loopers at 8.2 ± 1.3 cm/s and cyclonic loopers at 2.2 ± 1.1 cm/s. A general trend of anticyclones translating at close to the mean velocity of all drifters and faster than cyclones also holds for the eastern Caribbean and appears to be due to anticyclones being located within the main Caribbean Current in the central basin and the cyclones being located near the boundaries outside the regions of higher mean velocity. Anticyclones were observed to translate at very different speeds in different areas but at velocities similar to the mean velocity in these areas. The implication is that eddies were advected by the

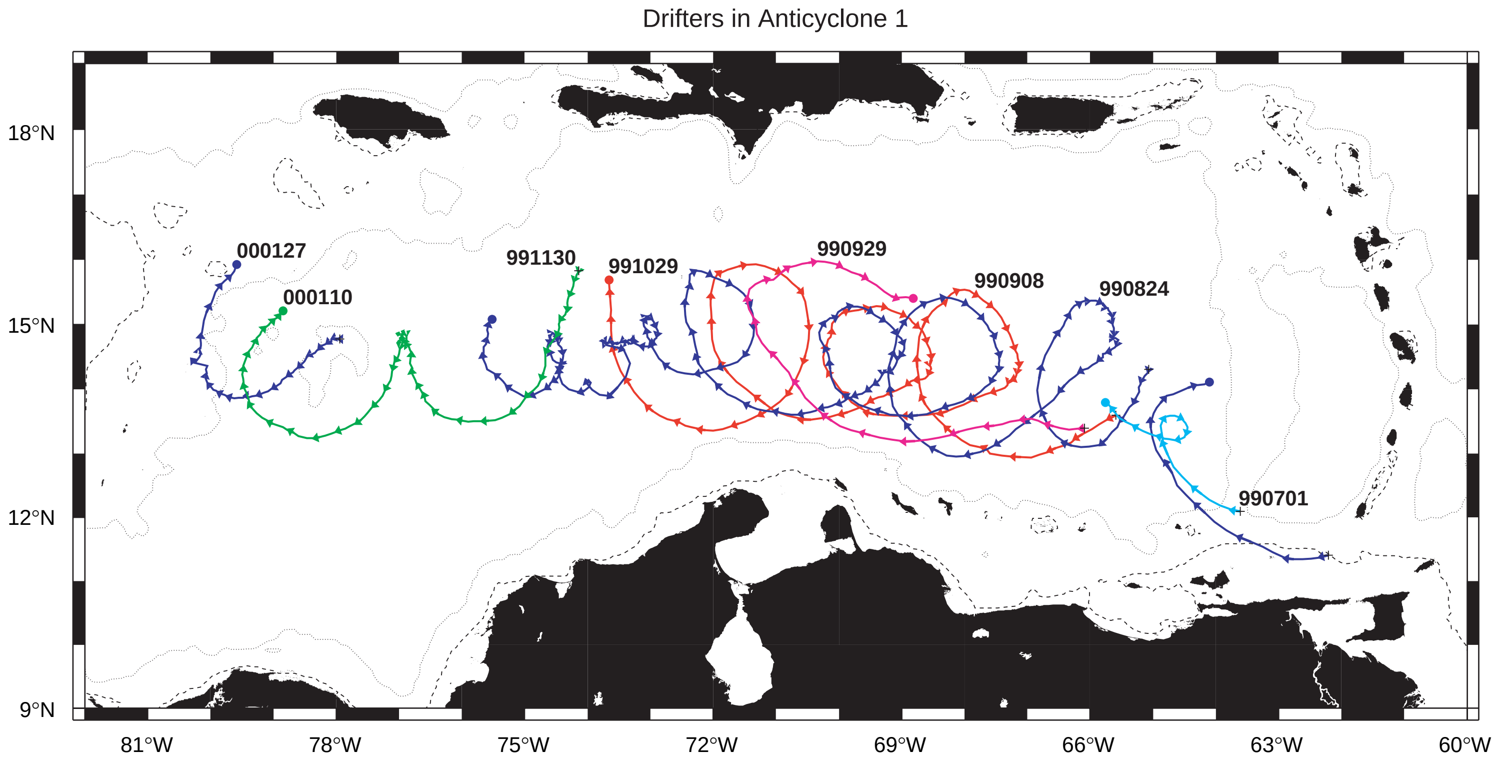

Fig. 9. Trajectories of five different drifters looping in and around anticyclone 1 during July 1999–January 2000 (Table 1). This anticyclone was tracked with drifters for nearly 7 months as it translated 1700 km across the Caribbean at an average velocity of 11 cm/s. The diameter of the largest loops was 300 km, around one-half of the north–south extent of the Venezuela Basin. Arrowheads are spaced at 1-day intervals. In mid-November, 1999, hurricane Lenny with winds of 135 knots translated eastward (near 15°N) just north of anticyclone 1 and generated energetic near-inertial oscillations in it with an amplitude of 75 cm/s and period near 2 days. These oscillations, which gradually decayed over 2 weeks, are superimposed on the anticyclone loops.

Table 1
Eastern Caribbean anticyclones

Anticyclone number	Days tracked	Number loops	Period (days)	Diameter (km)	Swirl velocity (cm/s)	U (cm/s)	V (cm/s)
1	119	8.5	14	167	43	−11.0	0.8
2	22	1.8	12	222	66	−11.0	−3.1
3	41	2.3	18	187	38	−21.4	0.7
4	70	4.2	17	109	24	−16.6	−0.7
5	101	7.3	14	108	28	−12.1	2.5
6	103	(10.8)	10	84	32	−10.0	3.2
7	51	2.7	19	235	45	−9.5	1.9
8	52	2.5	21	162	28	−13.6	5.2
9	56	3.0	19	265	52	−16.4	10.0
10	84	5.8	14	180	45	−12.8	5.5
Average			15.7±1.1	172±19	40±4	−13.4±1.2	2.6±1.2

Note: Average values (and standard errors) were calculated for the 10 major anticyclones in the eastern Caribbean (see Fig. 12). For anticyclone 1 the longest looper of the two identified was used in the estimates. Looping period of rotation was estimated by dividing the days of data by the number of loops. Swirl velocity was estimated from the square root of the sum of u and v velocity variances about the mean velocity in the x and y directions, assuming that most velocity variance was derived from the looping motion about the mean anticyclone advection velocity (U, V). Diameter was estimated from the swirl velocity times the period divided by π. The typical maximum swirl velocity in the anticyclones was around 60 cm/s, and the typical diameter of the largest loops was around 200 km. The Rossby number of the anticyclones using their average period of rotation is −0.25.

local background current in which they were embedded.

Details of the eddies are discussed below grouped into four regions—the eastern Caribbean (Venezuela and Colombia Basins), the Panama–Colombia Gyre, the western Caribbean southwest of Cuba, and the area of the Antilles Current in the northeast. The data in these regions were grouped and some statistics summarized in Table 2.

6. Eastern Caribbean anticyclones

The summary plot of loopers (Fig. 11) shows that the Venezuela and Colombia Basins are dominated by anticyclones (red trajectories). Some cyclones (blue) were observed there, but they are fewer in number and tend to be located near the boundaries. A box average of the central region between 65°W and 75°W reveals that 25% of all the data are in loopers and that 71% of these are anticyclonic. The mean westward velocity of the 10 anticyclonic loopers in the box is 14.4±2.5 cm/s compared to the mean velocity of all data in the box 15.4±0.9 cm/s. The three cyclonic loopers translated at 1.3±3.0 cm/s; the low mean velocity is due to the eastward translation of one cyclone near the southern boundary of Hispaniola and another cyclone that was stationary there. Both of these cyclones appear to have formed when anticyclones impinged on the southern coast of Hispaniola. The 10 main anticyclones in the eastern Caribbean are listed in Table 1. The average westward velocity of these is 13.4± 1.2 cm/s, and northward velocity is 2.6±1.2 cm/s based on grouping the 10 average velocities of the individual anticyclones.

Half of the anticyclone trajectories started in the far eastern Caribbean near or east of 65°W including two just inside the Lesser Antilles, one near 13.0°N 62.3°W and the other near 15.6°N 62.6°W (Fig. 11). This adds support to the hypothesis that the anticyclones form from remnants of NBC rings. Eight trajectories ended near the Jamaica Ridge, which appears to disrupt the typical eddy circulation so that the drifters ceased looping. Anticyclone 6 stalled near the ridge before the drifter stopped looping. The inferred anticyclone trajectories tend to lie along two bands near 15°N and 17°N, although three of the 15°N anticyclones drifted northwestward and merged

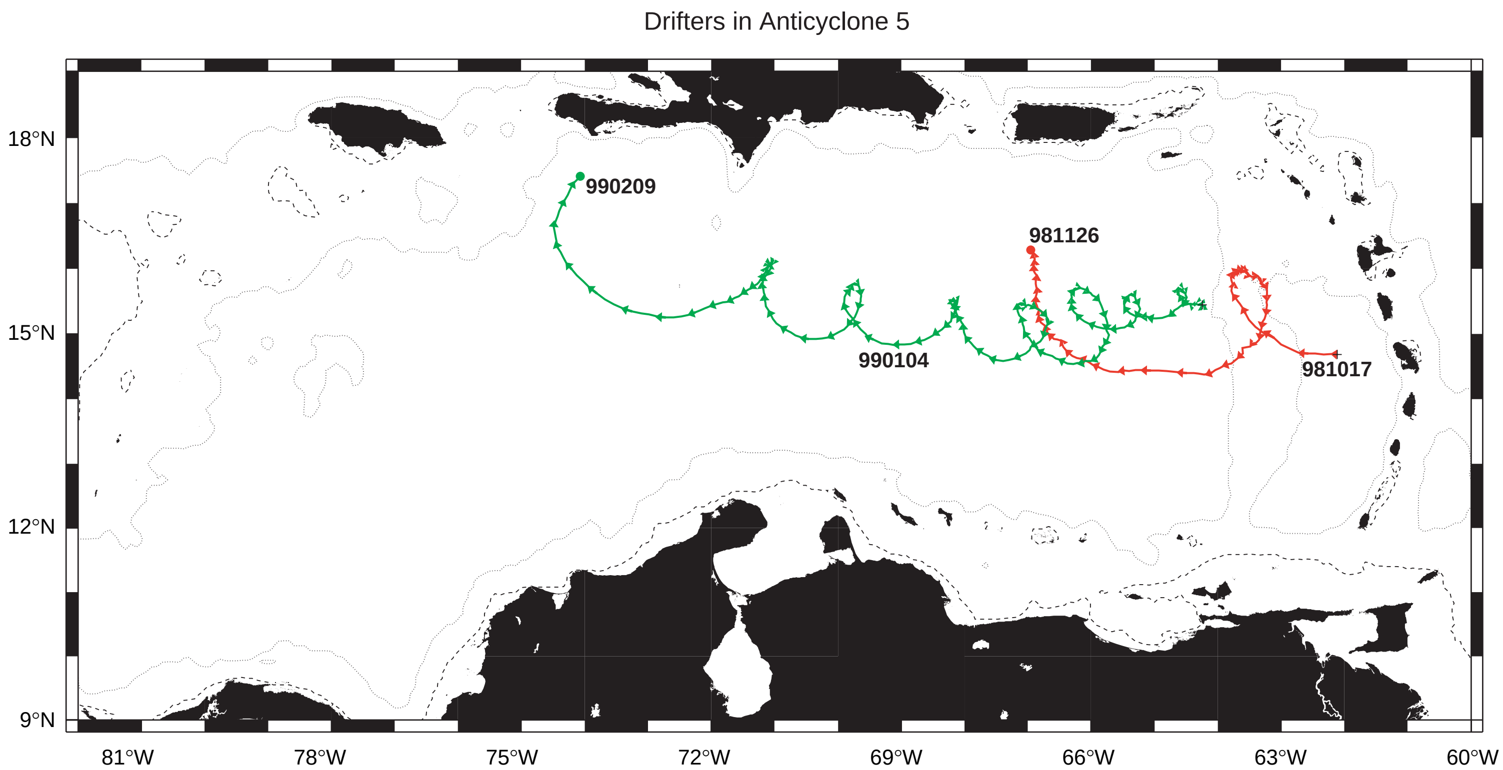

Fig. 10. Trajectories of two drifters looping in and around anticyclone 5. This anticyclone was tracked for nearly 4 months from October 17, 1998 to February 9, 1999 as it translated 1200 km through the Caribbean at an average velocity of 14 cm/s. The diameter of largest loops was around 200 km. Arrowheads are spaced at 1-day intervals.

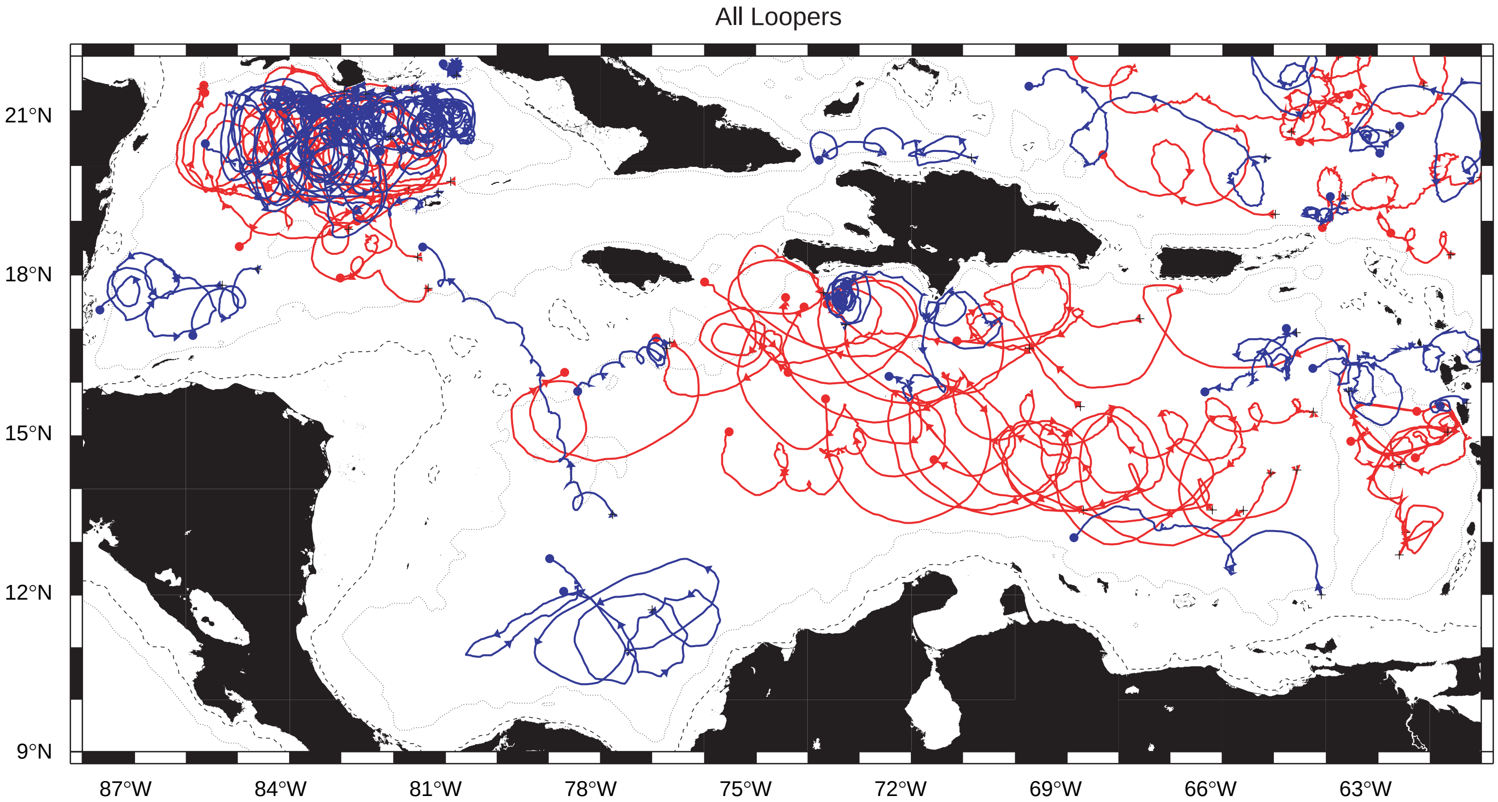

Fig. 11. Drifter trajectories in 28 cyclonic loopers (blue lines) and 29 anticyclonic loopers (red lines). Overall, 19% of the drifter data were loopers, and these were almost equally subdivided into cyclonic and anticyclonic, although different distributions were observed in different parts of the Caribbean. The eastern Caribbean (Venezuela and Colombia Basins) appears to be dominated by anticyclonic loopers, and cyclonic loopers are most often found near the boundaries there. Numerous cyclonic and anticyclonic loopers overlap southwest of Cuba. Arrowheads are spaced at 10 days.

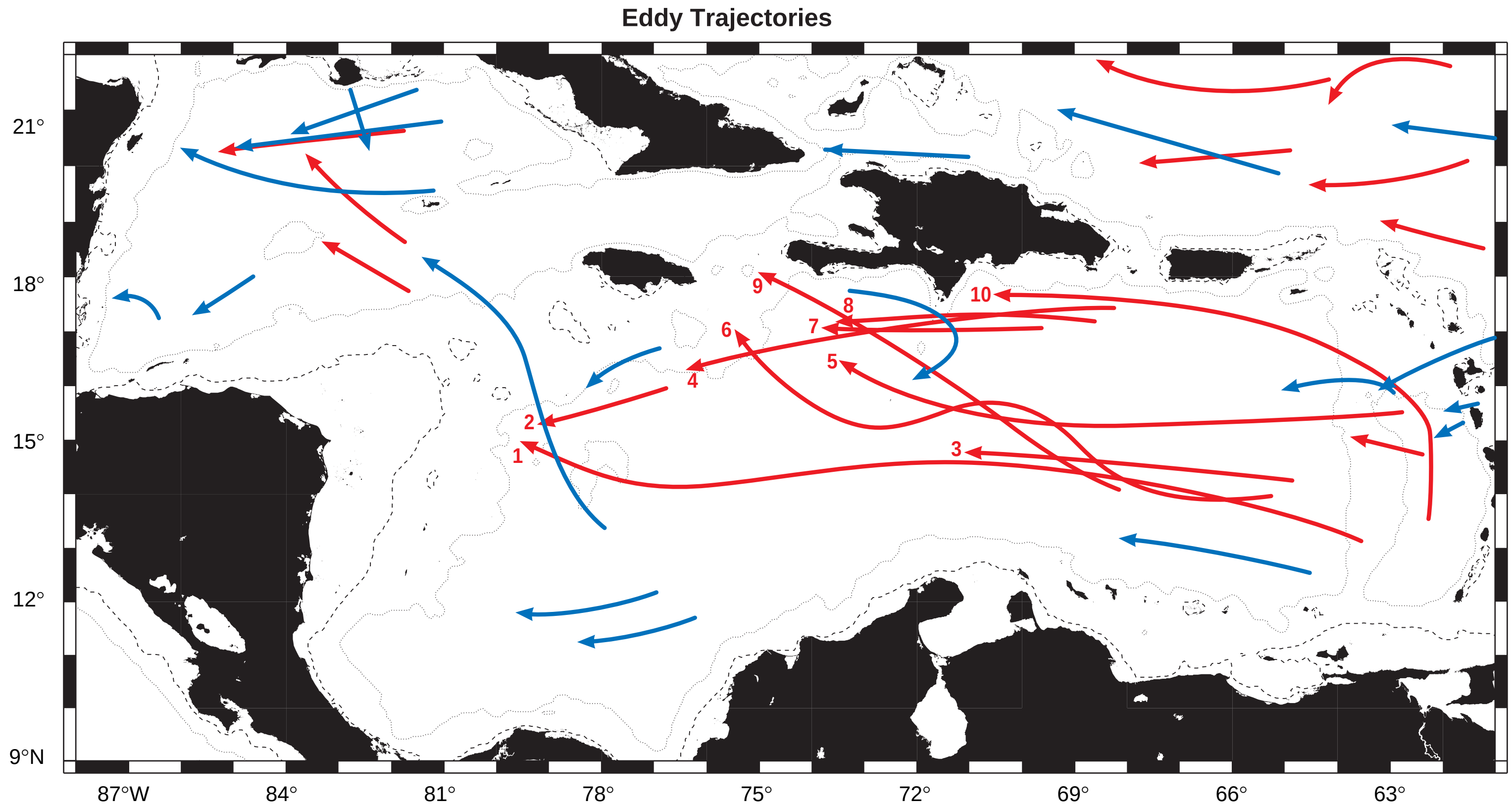

Fig. 12. Trajectories of 19 cyclones (blue) and 19 anticyclones (red) inferred from looping drifter trajectories. Trajectories were plotted only for eddies that clearly translated. Note the preponderance of anticyclones translating westward through the Venezuela and Colombia Basins as compared to the relatively few cyclones there. The anticyclones near 70°W appear to lie along two preferred paths centered near 15°N and 17°N, although three anticyclones near 15°N appear to translate northwestward and converge with the 17°N ones near 75°W near the Jamaica Ridge. Ten of the main anticyclones are numbered and details given in Table 1.

Table 2
Looper statistics

	Whole area 9–22°N 61–88°W	Eastern Caribbean 12–18.3°N 65–75°W	Western Caribbean 19–22°N 79–87°W	NE of Caribbean 18.3–22°N 61–74°W
Total data	73,332	14,196	15,104	14,061
% Loopers	19	25	38	14
% Anticyclones	50	71	37	53
All U (cm/s)	-9.1 ± 0.4	-15.4 ± 0.9	-2.0 ± 0.7	-4.9 ± 0.5
Loopers U	-5.2 ± 0.9	-10.6 ± 2.0	-1.6 ± 1.3	-4.7 ± 1.4
Anticyclonic U	-8.2 ± 1.3	-14.4 ± 2.5	-2.5 ± 2.0	-5.9 ± 2.0
Cyclonic U	-2.2 ± 1.1	-1.3 ± 3.0	-1.1 ± 1.6	-3.4 ± 2.1

Note: Four regions are listed including the whole area (Fig. 3) and three smaller subregions consisting of the Eastern Caribbean south of Puerto Rica and Hispaniola which contains 10 energetic anticyclones, the Western Caribbean southwest of Cuba containing numerous cyclones and anticyclones, and the Antilles Current region northeast of the Caribbean which has a mixture of cyclones and anticyclones. Mean eastward velocity (U) and standard error are listed for all the data in the region and for the loopers including anticyclonic and cyclonic. Northward velocity was omitted because it is usually smaller than the standard error and because the eddies translated mainly westward.

with the 17°N ones near the Jamaica Ridge southwest of Haiti (near 17°N 75°W). Curiously, the northern anticyclones translated at around the same speed as the southern ones despite faster westward velocities in the south.

The two bands of anticyclones appear to coincide with the structure of the mean velocity field. Specifically, the southern band of anticyclones coincides with anticyclonic shear located on the northern side of the main Caribbean Current as shown by red arrows in Fig. 7. The northern band of anticyclone trajectories lies near the northern edge of the northern band of red arrows near 17°N (Fig. 7). The two bands of anticyclones merge where the northern current increases in speed as shown by an increased number of red arrows in Fig. 7 near 75°W.

A meridional velocity profile across the eastern Caribbean (65–75°W) using drifter data but excluding loopers (Fig. 13, right panel) clearly shows two jets or maxima in the westward flow, one of 34 ± 6 cm/s centered near 13°N, the other of 19 ± 2 cm/s centered near 17°N, bounded on the north by slow eastward flow $\sim1\pm3$ cm/s. The equivalent profile using only looper data (Fig. 13, left panel) has a similar structure, a maximum of 49 ± 7 cm/s near 13°N, a second maximum of 18 ± 5 cm/s near 17°N, bounded on the north (near 18°N) by swift $\sim26\pm12$ cm/s eastward velocity. The swift eastward current near 18°N is caused by the northern, eastward-flowing, part of the anticyclones that impinge on the southern boundaries of Hispaniola and Puerto Rico. Data grouped quarterly into 1-degree north–south bands between 65°W and 75°W suggest that the two jets shown in the $\frac{1}{2}$-degree profile using non-looper data exist throughout the year.

The similarity of velocity profiles raises the issue of the relationship between the anticyclones and the westward jets. One possibility is that the anticyclones cause the maxima and minima in the mean velocity profile. The looper velocity profile in Fig. 13 shows that the swirl velocity of anticyclones, which is westward south of the eddy center and eastward north of the center, in combination with the westward translation of the eddy center results in a rectified mean velocity profile that looks like the mean velocity profile created by excluding the loopers. Presumably, some other drifters that were not classified as loopers were advected by the outer portions of the anticyclones and contributed to the mean (rectified) velocity profile created by excluding loopers. The idea is that the two bands of anticyclones add the double-jet structure to the Caribbean Current, which without the anticyclones might gradually increase in westward velocity toward the south. A second possibility is that the Caribbean Current, independent of anticyclones, consists of two westward jets and that the anticyclones form and

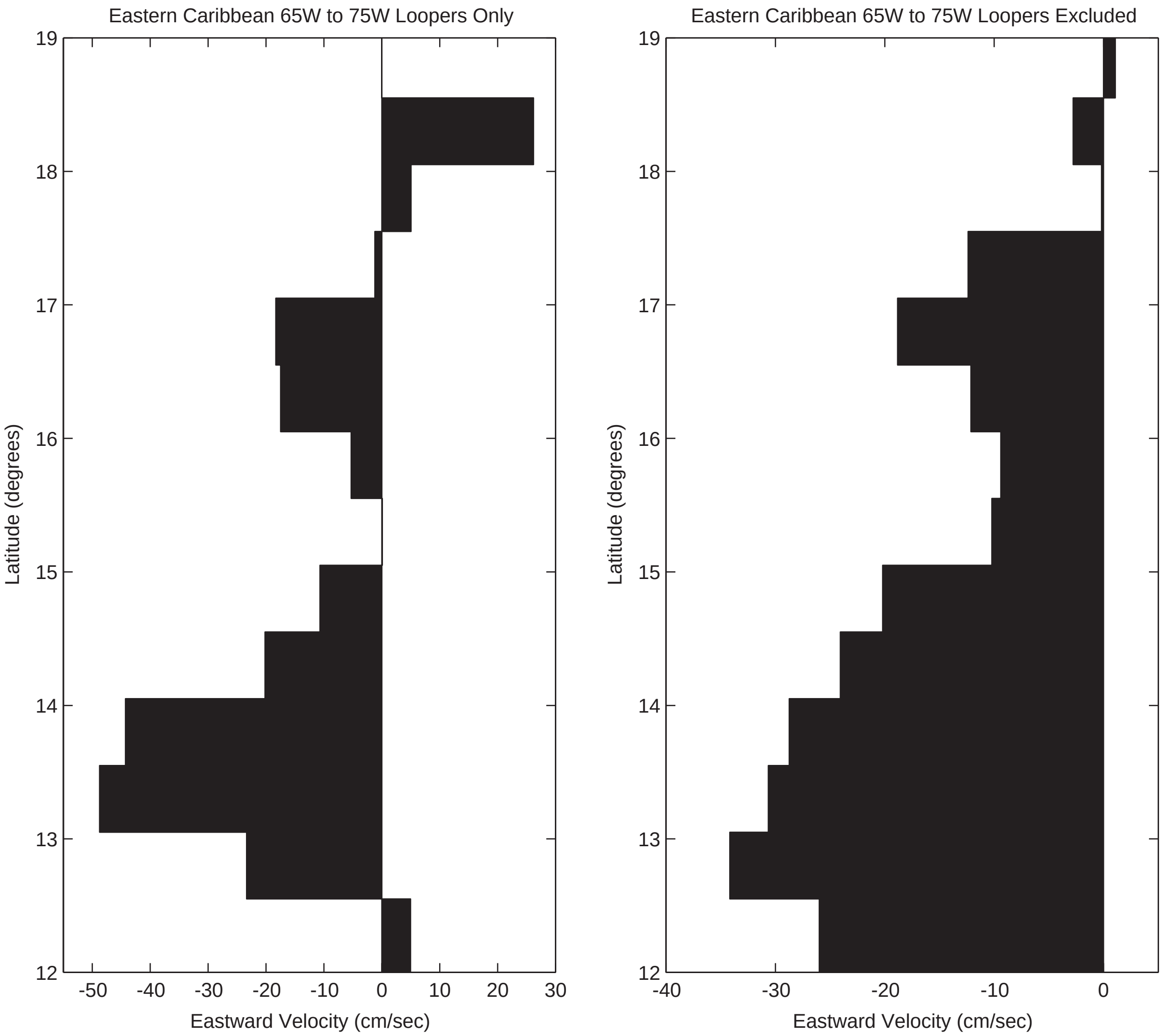

Fig. 13. Meridional velocity profile of eastward velocity averaged by grouping individual velocities in $\frac{1}{2}$-degree north–south bins in the central Caribbean (65–75°W). Note the similar double-jet structures of the profile created using only looper data and the profile using non-looper data.

grow located in the anticyclonic shear on the northern edge of the jets. The EKE of the anticyclones increased around 37% as they translated westward, from around $676\,\mathrm{cm}^2/\mathrm{s}^2$ near 62.5°W (averaged in 3-degree longitude bins) up to $923\,\mathrm{cm}^2/\mathrm{s}^2$ near 74.5°W, which lends support to the second possibility and is consistent with the results of an altimetric study which suggested that anticyclones intensified toward the west (Carton and Chao, 1999).

Estimates were made of the energy exchange between the eddies and the mean field using $\rho\langle u'v'\rangle\partial U/\partial y+\rho\langle v'v'\rangle\partial V/\partial y$ (and omitting other terms), which expresses the production of EKE by interaction of the turbulent Reynolds stresses with the shear of the mean flow and vice versa, where u' and v' are fluctuations of velocity about the mean velocity U and V and $\langle\ \rangle$ indicates an average (see Hansen and Paul, 1984). Results using data in 0.5-degree bins between 65°W and 75°W suggest a conversion of EKE to mean kinetic energy and standard error $\sim 0.30 \pm 0.26 \times 10^{-3}\,\mathrm{erg/cm^3\,s}$ south of the southern jet maximum and near the southern boundary 12.0–13.0°N. North of this between 13.0°N and 18.5°N is a conversion of mean flow kinetic energy to eddy energy $\sim 0.12 \pm 0.11 \times 10^{-3}\,\mathrm{erg/cm^3\,s}$. The ratio of the eddy energy to the eddy production in the region 13.0–18.5°N suggests a time scale of 49 days, which can be interpreted as the e-folding time of exponentially growing eddies.

Previous studies of hydrographic sections across the Caribbean also have observed two westward jets (Gordon, 1967; Morrison and Nowlin, 1982), and a recent velocity section across the Caribbean near 66°W in September 1997 also clearly showed two westward jets, one of 120 cm/s near 13°N and the other of 20 cm/s near 17°N separated by nearly zero flow near 15–16°N (Hernandez–Guerra and Joyce, 2000). The southern jet contained water from the Orinoco River, the tropics, and the South Atlantic. The northern one contained Caribbean surface water and subtropical underwater with sources in the North Atlantic. We are not aware of any observations or any model simulations that reproduce the two bands of anticyclones, although there is an indication of a double-jet structure of the Caribbean Current in some (Murphy et al., 1999; Fratantoni et al., 2000). Fratantoni et al. (2000) and also Johns et al. (2002) discussed three simulations that showed (1) the wind-driven transport (no MOC) from the North Atlantic to be concentrated in the northern part of the Venezuela Basin, (2) the MOC-driven transport (no wind) from the South Atlantic to be concentrated in the southern part of the basin, and (3) the wind-plus-MOC-driven circulation to have transport concentrations in both the northern and southern parts, implying the existence of two distinct jets.

Eastward or counterflows in the Caribbean have been repeatedly reported (Gordon, 1967; Roemmich, 1981; Morrison and Nowlin, 1982; Smith and Morrison, 1989; Morrison and Smith, 1990; Johns et al., 1999). In order to search for substantial counterflows in the drifter data, all eastward velocities over 30 cm/s were plotted (Fig. 14). Major clusters of eastward velocity are located in two areas of mean eastward currents, the southern Panama–Colombia Gyre and the Yucatan Current that flows northeastward. Three other clusters are associated with Caribbean eddies. One is southwest of Cuba concentrated near the Isle of Pines. A second is centered between 17.0°N and 18.3°N just south of Hispaniola. A third is centered between 15.0°N and 16.5°N in the mid-Colombia Basin. A plot of eastward speeds over 30 cm/s in loopers (not shown) suggest that these three clusters are caused primarily by the eastward component of the eddy swirl velocity. In particular, the two clusters in the eastern Caribbean appear to match the northern parts of anticyclones. Although there could be eastward flows not associated with eddies, the matching of the swift eastward eddy swirl speeds with the clusters of eastward velocities suggests these counterflows are caused primarily by the eddies. Therefore, most occurrences of fast eastward flow in the Caribbean outside of the Panama–Colombia Gyre and Yucatan Current are likely due to the swirl velocity of Caribbean eddies, and in the eastern Caribbean mainly anticyclones.

The looper data were used to estimate the population and formation rate of anticyclones in the eastern Caribbean. In 1998, four anticyclones were tracked with drifters, including two sets of two anticyclones tracked simultaneously (numbers 3 and 10, 4 and 5, Table 1). Since some anticyclones could have been missed, this implies a minimum formation rate of four anticyclones per year. In the box bounded by 65°W and 75°W anticyclonic loopers comprised 17.5% of all the drifter data. This implies that around 17.5% of the area, which is around 108,000 km^2, comprised anticyclones. If the typical overall diameter is 250 km, then there should be a population of around 2.2 anticyclones in the box at any one time, in agreement with the two pairs of tracked anticyclones. At a typical speed of 13.4 cm/s anticyclones translate through the box in around 3.0 months, which suggests a formation rate around eight anticyclones per year. Choosing a smaller diameter of 200 km results in around 12 anticyclones per year. The 8-per-year rate matches that of NBC rings observed to translate toward the Caribbean Islands (Johns et al., 2003), consistent

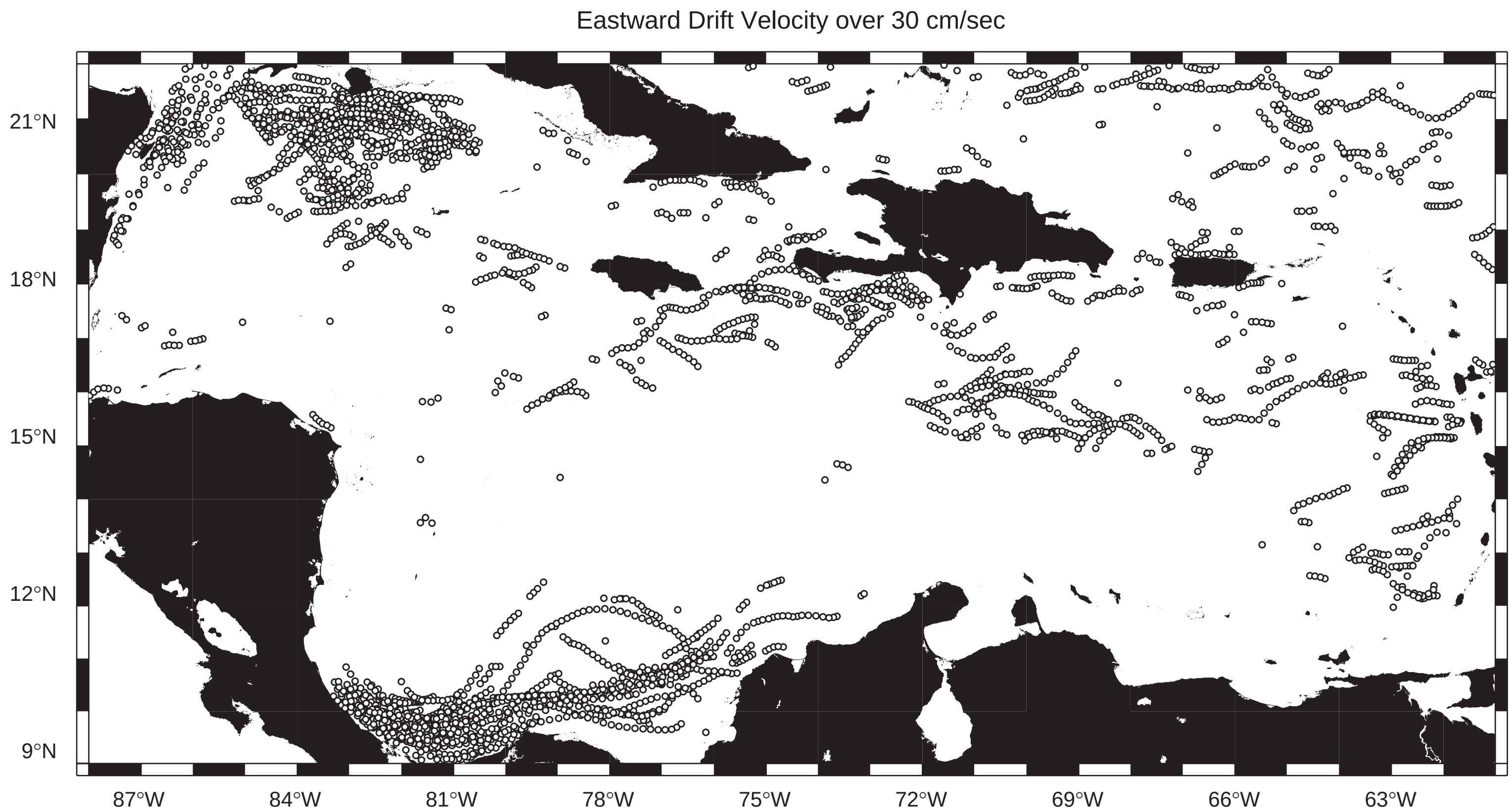

Fig. 14. Locations of eastward drifter velocity components that are faster than 30 cm/s, indicating regions of counterflows. Plots of slower eastward velocities were also generated, but those clusters of eastward velocity tended to be more diffuse.

with the hypothesis that the anticyclones form from remnants of the rings.

The number of looping days in anticyclones (and the percentage of total data in anticyclones) varies seasonally from low values, down to 17 days during February–April, to high values, reaching 136 days during September–November (Fig. 15). The implication is that more anticyclones form during summer and fall than during winter and spring, or possibly the anticyclones are more intense and better able to trap drifters in their swirl velocity during the months of September–November.

The inferred seasonal variation of anticyclone population might be related to variations in the velocity of the Caribbean Current (and current shear), which could modulate anticyclone growth. The Caribbean Current is maximum during July and minimum during November (Fuglister, 1951; Johns et al., 2002); the 3-month lag between maximum currents and maximum number of anticyclones could be the time required for anticyclones to become sufficiently energetic and trap particles in closed circulation. Although there is no obvious seasonality in the number of NBC rings formed, rings that form after the summer NBC maximum transport and while the retroflection is still clearly established (November–February) appear to be larger and deeper than those at other times (Johns et al., 2003). This seasonality in ring structure together with variations of Caribbean inflow might influence how long rings take to penetrate into the Caribbean, resulting in seasonality of Caribbean anticyclones.

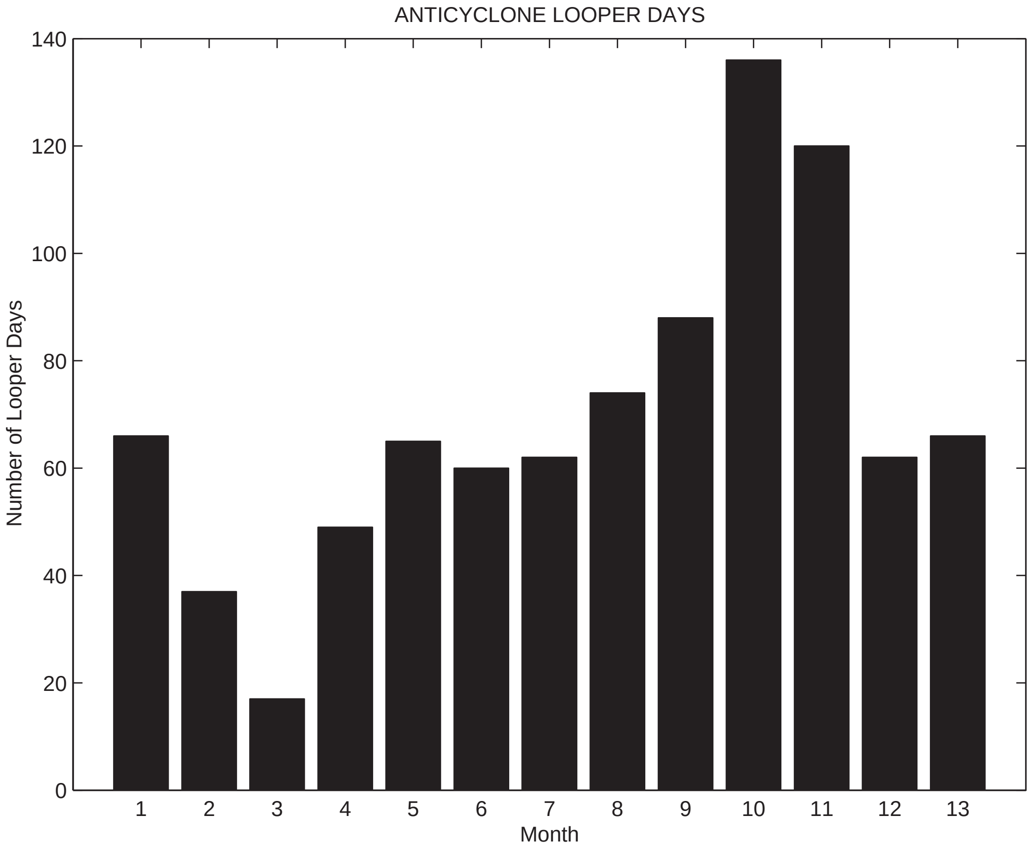

Fig. 15. Number of looper days in the 10 main anticyclones in the eastern Caribbean (Table 1). The longest looper of the two available was used for anticyclone 1.

In summary, several characteristics of the anticyclones observed in the eastern Caribbean suggest they could have formed from the anticyclonic remnants of NBC rings. First, the anticyclones first appeared in the eastern Caribbean just west of the Antilles where rings collided with the islands and disappeared. Second, the estimated formation rate and the measured translation rate of anticyclones are very similar to those of rings. Third, the swirl velocity and rotation rate of anticyclones are about half that of rings and the overall diameter of the anticyclones is somewhat smaller than that of rings. These observations are consistent with the concept that a ring's vorticity decays somewhat in passing through the Antilles so that anticyclones formed on the inside of the islands from ring remnants would be weaker than the original rings. Fourth, the anticyclones appear to lie in two bands that coincide with westward jets of the Caribbean Current, implying that anticyclones are energetic components of the circulation. However, if anticyclones form on the northern anticyclonic shear side of the jets from instabilities of the Caribbean Current, then we would also expect to see cyclones form along the cyclonic shear sides of the jets, which we do not (except for one cyclone near the southern boundary of the Venezuela Basin). It is possible that instabilities of the anticyclonic shear of the jets help organize and amplify the injected anticyclonic vorticity of rings, and this could contribute to the energy and longevity of the anticyclones and their observed amplification as they translate westward.

How could NBC ring water pass through island passages and reform as an anticyclone? Results of a laboratory study of an eddy colliding with several seamounts shows that water can be peeled off the outer part of the eddy, pass between seamounts as a streamer, and reform into an eddy (or two eddies) on the other side of the seamounts Cenedese and Adduce (2002) see also Cenedese (2002) and Wang and Dewar (2003). Streamers from some eddies passed through two passages and sometimes two eddies formed. The diameter of the central portion of a ring, inside the maximum swirl velocity, is around 200 km. This amount of water could pass through a typical 40-km wide island passage at 30 cm/s (see Wilson and Johns, 1997) in around 30 days, which seems consistent with what we know about rings. Some rings collided with the southern Caribbean islands and disappeared rapidly in around a month; other rings passed northward to 15–18°N where they decayed or disappeared over a few months just east of the islands.

There is very little direct evidence from drifters of NBC ring water forming an anticyclone inside the Caribbean. The best evidence comes from a single drifter that had been looping in an NBC ring located east of the islands (Fig. 16). The drifter looped and translated toward the island arc, passed between Dominica and Guadeloupe Islands, made two small (20 km) cyclonic loops immediately west of Dominica and then one-and-a-half larger (140 km) anticyclonic loops and a cusp in what could have been an anticyclone forming inside the Caribbean (red trajectory). The drifter then meandered westward through the Venezuela Basin leaving no further clues about the possible anticyclone.

High-resolution numerical models of ring-like eddies colliding with islands suggest that some eddies can pass coherently through the island passages when the eddy diameter is much larger than the islands and passages (Simmons and Nof, 2002; Garraffo et al., 2003). Garraffo et al. report that inside the Caribbean the simulated sea-surface height anomalies are generally smaller than those of rings, the anomalies propagate westward, and they often originate as part of a ring that remains for some time east of the Antilles.

It is also possible that local wind stress curl can form anticyclones. Oey et al. (2003), using a numerical simulation of Caribbean circulation, found that a patch of anticyclonic wind stress curl located southwest of Hispaniola can force a depression of isopycnals through Ekman pumping, resulting in an anticyclone. These "Hispaniola anticyclones", as Oey et al. call them, subsequently drifted westward through the Caribbean at a rate of about 3–4 per year. Some of the drifter-tracked anticyclones started farther east than Hispaniola, but perhaps they could have been augmented by this process in the region southwest of Hispaniola.

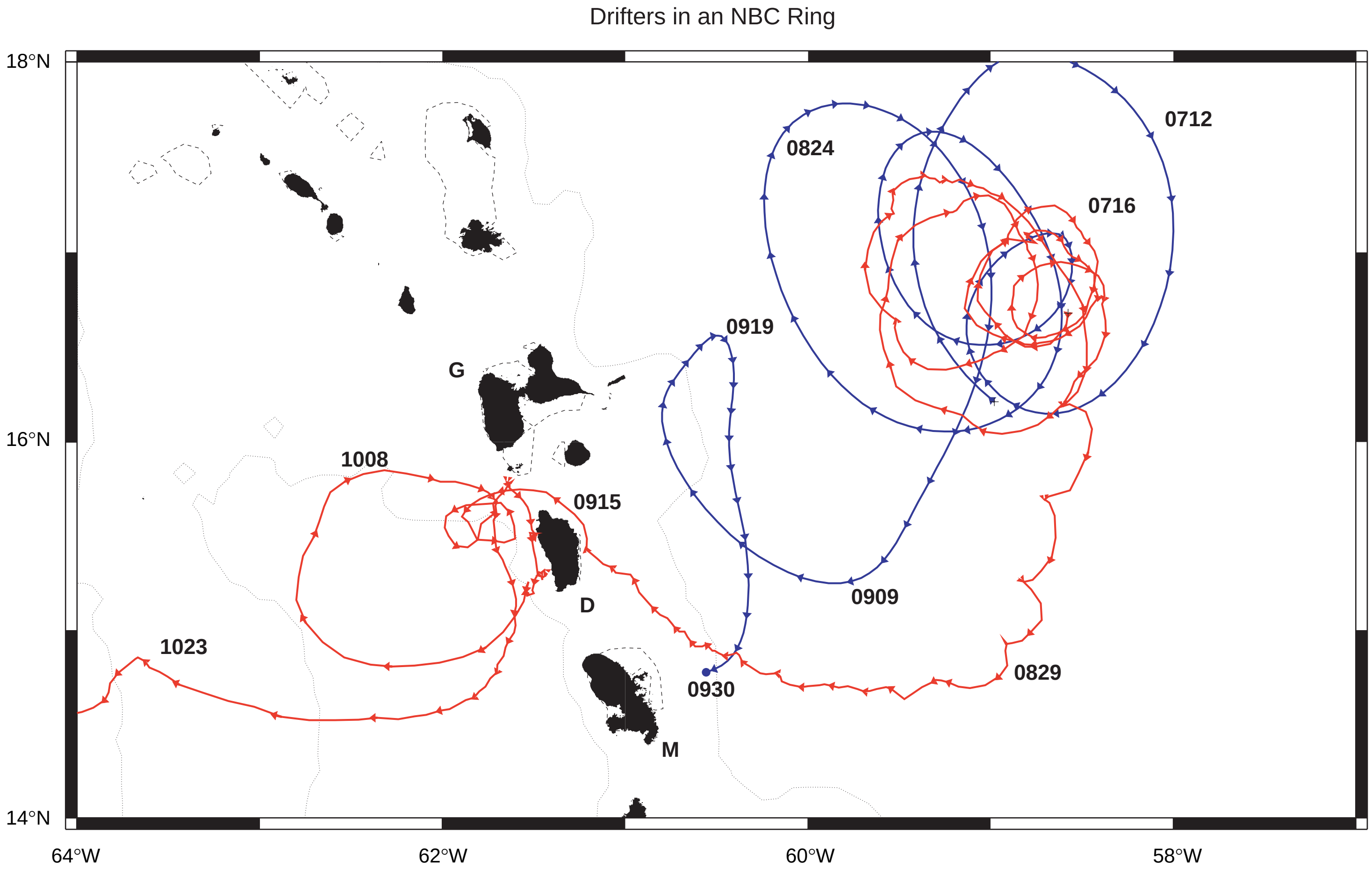

Fig. 16. Two drifters looping in an NBC ring that translated southwestward toward the islands of Guadeloupe (G), Dominica (D), and Martinique (M) during July–September 2000. One drifter (red) entered the Caribbean between Guadeloupe and Dominica and made one-and-a-half anticyclonic loops plus a cusp implying that some ring anticyclonic vorticity entered the Caribbean and was forming an anticyclone there. The data from the other drifter (blue), an undrogued RAFOS float, contained gaps, and the float could not be tracked with adequate resolution in the Caribbean. Its trajectory adds evidence that the ring translated southwestward up to the islands. Some small ~15-km anticyclonic cusps in the red trajectory in August are interpreted to be near-inertial oscillations (~2-day period). Arrowheads are spaced at 1-day intervals.

7. Other eddies

7.1. Eastern Caribbean cyclones

All of the cyclones in the eastern Caribbean appear to begin or to lie near topographic features of the basin. The cyclone near the southern side of the Venezuela Basin, translating westward at 21 cm/s, could have been generated by the cyclonic shear on the southern side of the main Caribbean Current where it flows along the boundary. Two loopers in different cyclones south of Hispaniola began looping where the eastward swirl velocity of two different anticyclones impinged on the southern coast of the island; one cyclone remained stationary, the other was advected clockwise around the anticyclone, eastward along the coast then southward. Both cyclonic loopers began with small ~10–50-km diameters and fast 1.5–4.0-day loops ($Ro = 2.2 - 0.8$), which gradually increased in diameter and period. Two cyclonic loopers began near passages through the eastern islands, and two others were located just inside these islands, implying that cyclones are often formed by flows through the passages. Two other cyclones with small loops were observed in the western Colombia Basin one of which passed over the Jamaica Ridge.

7.2. Panama– Colombia Gyre cyclones

Two cyclones were observed in the eastern part of the cyclonic gyre near 11.5°N 77.5°W (Fig. 11). They translated westward at 3–5 cm/s toward the central part of the gyre. Swirl speeds of 38 cm/s were located at a diameter of around 200 km and the period of rotation was around 20 days ($Ro =$ 0.26). The cyclones were observed in 1998 and 1999 during the months of September–December, suggesting seasonality. Another cyclone was observed with altimetry in the gyre near 14°N during August–November 1993 by Andrade and Barton (2000).

Three possible formation mechanisms are suggested. The first is that the cyclones could have formed on the southern cyclonic shear side of the main Caribbean Current jet as it flows westward away from the coast of Colombia. The second is that they could have formed as pieces of the eastern part of the gyre that temporarily separated from the more intense western part. The third is that they could have been formed as inverse (modeled) "Hispaniola anticyclones" by a local maximum in the wind stress curl that coincides with the cyclones (Chelton et al., 2004; Oey et al., 2003). Andrade and Barton (2000) suggested that cyclones form seasonally during the part of the year when strongest meridional gradients in salinity and wind occur.

7.3. Western Caribbean eddies

Two cyclones (diameter ~100 km, swirl velocity ~30 cm/s) were observed in the southern part of the western basin, and they presumably formed there on the southern, cyclonic shear side of the Caribbean Current. The region north of this and southwest of Cuba is dominated by 10 cyclonic loopers and nine anticyclonic loopers. In the region 19–22°N 79–87°W, 38% of the data are in loopers, and 63% of these are cyclonic. The mean westward velocity of all loopers in the box is 1.6 ± 1.3 cm/s, indistinguishable from the mean of all the drifters 2.0 ± 0.7 cm/s. The implication is that slow background zonal flow caused the slow translation of eddies there.

The loopers in the box 19–22°N 79–87°W were located in seven different cyclones and six different anticyclones. Eight loopers were located in a cyclone–anticyclone pair, which translated slowly (~2 cm/s) westward. The three longest looping drifters in the Caribbean were in this pair, the longest two at 8.6 and 7.9 months in the cyclone. Fig. 17 shows a summary of the loopers in the cyclone and anticyclone and four monthly summaries of trajectories in these eddies during November 1999–February 2000. The anticyclone center was located around 200-km west of the cyclone center. On several occasions drifters looping around one eddy of the pair began to loop around the other eddy, suggesting that the near-surface swirl velocity of the two eddies was connected. The drifters began to loop in the eddies in October 1999 when launched. The anticyclone translated westward and appeared to coalesce with the Yucatan Current in February 2000 when the

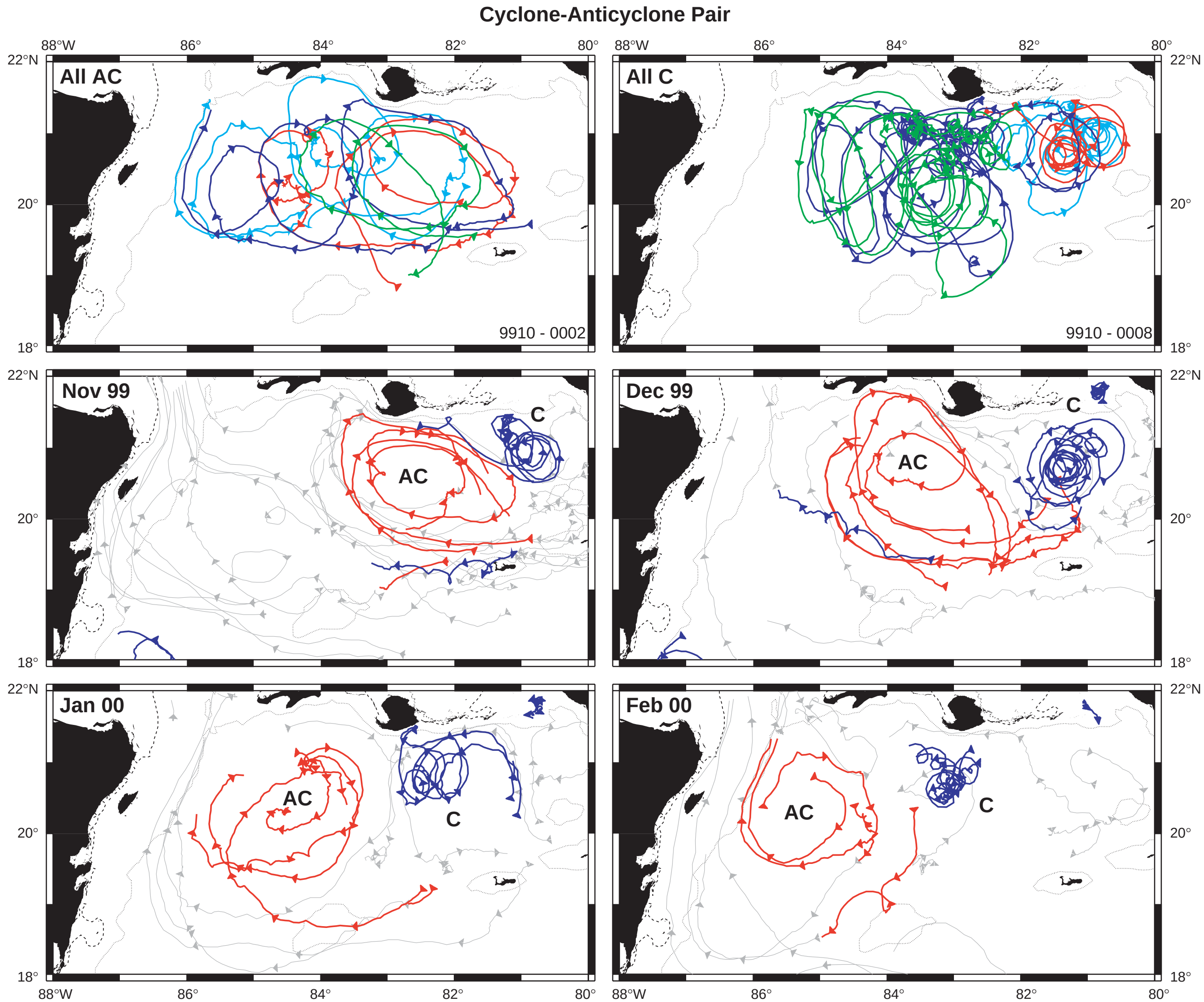

Fig. 17. Summaries of four loopers in the cyclone (C) and four in the anticyclone (AC) of a cyclone–anticyclone pair southwest of Cuba, and four monthly plots of loopers in the cyclone (blue)–anticyclone (red) pair as they translated westward toward the Yucatan Current. Background drifters (non-loopers) are colored gray. Two additional small cyclonic loopers are seen; one began near Grand Cayman Island near 19.3°N 81.0°W in November 1999 and another is located in the northeastern corner in December–February. Arrowheads are spaced at 5 days.

drifters accelerated to the north. The cyclone translated westward until August 2000 when it was located near 20.8°N 84.5°W and the drifters stopped looping. It is possible that the cyclone also coalesced with the Yucatan Current. The cyclone's lifetime was at least from mid-October to the end of August 2000, a total of 10.5 months and a record for Caribbean eddies.

The overall diameter of the anticyclone was ~200 km, its fastest swirl velocity was ~40 cm/s, and its period ~30 days ($Ro \sim -0.1$). The loopers in the cyclone began in October 1999 with small ~10-km loops, which increased to around 100 km during December 1999–April 2000 and to around 200 km afterward. Maximum swirl speeds were around 30 cm/s at 10-km diameter, increasing to 60 cm/s at 60-km diameter in November 1999 and at 200 km during May–July 2000. The period of rotation increased from around 1 day ($Ro \sim 3$) for the early small 10-km loops up to around 17 days ($Ro \sim 0.2$) at 200-km diameter at the end.

The western Caribbean anticyclones were observed northeast of the main Caribbean Current on its anticyclonic shear side, which suggests that they could have formed from instabilities in this region. It is also possible that anticyclonic vorticity from the eastern Caribbean anticyclones was advected over the Jamaica Ridge and reformed as western anticyclones, perhaps amplified by the anticyclonic shear there.

A possible formation mechanism of the cyclone in the northern Yucatan Basin is suggested by the drifter that began to make rapid (~1-day period), small (10-km diameter) cyclonic loops when the northern part of the anticyclone (of the anticyclone–cyclone pair) impinged on the southern boundary of Cuba near the Isle of Pines (near 83°W). Swift 70–80 cm/s eastward flow measured by two drifters within 3 km of the Isle of Pines is interpreted to have created intense cyclonic shear, which resulted in the formation of a small intense cyclone. The cyclone was advected to the eastern side of the anticyclone where, by the end of November, the cyclonic loops increased in diameter to around 60 km and the period of rotation increased to 3 days ($Ro \sim 0.9$). Another drifter in the anticyclone started to loop cyclonically near the same place as the first but 15 days later (Fig. 17, November panel) and merged with the loops of the first cyclonic looper. Two additional cyclonic loopers were in this cyclone, which eventually reached a diameter of 200 km. Four other drifters near the southern coast of Cuba made small cyclonic loops there, three of them when other nearby drifters indicated larger-scale anticyclonic motion near the coast of Cuba. These observations are similar to those near Hispaniola and may indicate an important formation mechanism of cyclones. The two successive cyclonic loopers that merged in the cyclone suggest that a series of small intense cyclones began near the Isle of Pines, that the cyclones were advected eastward by the swirl velocity of the anticyclone, and that the cyclones coalesced growing into a larger long-lasting cyclone. Drifters in the anticyclone and that passed within around 10 km of the Isle of Pines tended to loop in the cyclone; those farther away tended to continue to loop in the anticyclone. Due to its slow translation, the anticyclone interacted continuously with the Isle of Pines for 3 months, which appears to be sufficiently long for a series of cyclones to form, collect, and grow into the large energetic cyclone observed.

Rather similar small cyclones (40–50-km diameter) have been observed in the vicinity of warm core Gulf Stream rings, possibly formed by their interactions with the continental margin there (Kennelly et al., 1985). Some other similar cyclones, called frontal eddies and spin-off eddies, also have been observed along the left edge of the Loop Current, Florida Current, and Gulf Stream (looking downstream), although the eddies are usually advected rapidly downstream unlike the cyclones observed southwest of Cuba (see e.g. Lee, 1975; Lee and Atkinson, 1983; Lee et al., 1991; Fratantoni, 1998; Fratantoni et al., 1998). The large size, small translation velocity, and long life of the Cuba cyclone appear to be different from these other cyclones.

7.4. Eddies Northeast of the Caribbean

Northeast of the Caribbean in the upper right-hand corner of the large box (Fig. 11) is located six anticyclones and six cyclones including a cyclone just north of Hispaniola translating toward

Windward Passage. In this area (18.3–22.0°N 61–74°W), 14% of the data are loopers and 53% are anticyclones. The mean westward velocity of all the data is 4.9 ± 0.5, of looper data 4.7 ± 0.5 cm/s, of anticyclones 5.9 ± 2.0 cm/s, and of cyclones 3.4 ± 2.1 cm/s. Typical (median) values of swirl speeds are 20 cm/s, diameters are 100 km, and periods of rotation are 18 days ($Ro = 0.16$), although a few cyclonic loopers were significantly smaller and rotated faster than this.

8. Summary

Two hundred and twelve drifter trajectories were used to characterize the mean currents in the Caribbean and its variability. Different geographical patterns of trajectories and drifter speeds suggested some characteristics of the flow field that were shown more quantitatively in maps of the mean velocity and EKE. The Caribbean Current was traced as a high-speed current (>25 cm/s) westward through the southern part of the Caribbean except where it merged with the counterclockwise flow of the Panama–Colombia Gyre in the mid-Colombia Basin. A second band of westward velocity (25–30 cm/s) observed in the northern Caribbean just south of Hispaniola merged with the main southern Caribbean Current near 75°W. The northern band was traced eastward to the Antilles where water enters from the North Equatorial Current and from some NBC rings. The southern band was traced to the southeastern Caribbean where South Atlantic Water enters including some from NBC rings.

Drifter trajectories with two or more loops were identified as eddies and subdivided into cyclonic and anticyclonic loopers. Overall, 19% of the data were in a total of 57 loopers, 29 anticyclonic and 28 cyclonic. The loopers were considered to have been located in 49 different eddies, 24 anticyclones and 25 cyclones. The eastern Caribbean is dominated by energetic anticyclones with typical swirl speeds of 60 cm/s, diameters of 200 km, and periods of rotation of 16 days. The anticyclones translated westward at around 13 cm/s up to the Jamaica Ridge where the drifters stopped looping implying that the eddies were disrupted by topography. The anticyclonic looper data suggest a formation rate of around 8–12 anticyclones per year with possibly more during September to November and fewer during February to May.

Probably the most significant findings are that in the eastern Caribbean there are two bands of anticyclones that match two bands of swift westward flows or jets in the Caribbean Current; that the northern one originates (primarily) in the wind-driven flow of the North Atlantic; and the southern one originates in the MOC-forced flow coming from the South Atlantic. The anticyclones appear to form in the far eastern Caribbean from remnants of NBC rings that collided with the Lesser Antilles; the anticyclones were perhaps amplified by instabilities of the anticyclonic shear of the Caribbean Current jets.

Cyclones tended to be located near the boundaries in the eastern Caribbean, and it is suggested that they formed on the cyclonic shear side of the Caribbean Current or in the cyclonic shear zone created when the swirl velocity of anticyclones impinged on Hispaniola. Some small cyclones were formed as water squirted through the passages of the Lesser Antilles.

Eastward flows greater that 30 cm/s were observed in the eastern Caribbean. The southern Panama–Colombia Gyre with its swift mean eastward flow stands out among these. Two other clusters of eastward velocity coincide with the northern eastward swirl velocity of anticyclones located in the two bands. Although there could be countercurrents not associated with anticyclones, the two clusters suggest that a major source of eastward currents are anticyclones.

The western Caribbean area southwest of Cuba was dominated by loopers. Thirty-eight percent of the data were in 19 loopers, including 10 cyclonic and nine anticyclonic. Eight loopers were located in a cyclone–anticyclone pair that translated slowly ~2 cm/s westward toward the Yucatan Current, where both eddies disappeared and probably coalesced with it. The anticyclone possibly formed from anticyclonic vorticity advected over the Jamaica Ridge from eastern Caribbean anticyclones, enhanced by the anticyclonic shear of the Caribbean Current in the western Caribbean. The cyclone is thought to have formed when the northern part of the anticyclone impinged on the Isle of Pines creating strong cyclonic shear and a series of small intense cyclones, which were advected eastward and coalesced into a larger cyclone. Nine drifters began looping cyclonically in small rapid loops (down to around a 1-day period) near topography suggesting this could be a frequent source of cyclones in the Caribbean.

The westward translation velocity of anticyclones varied from around 13 cm/s in the eastern Caribbean to around 2 cm/s just south of Cuba. The velocity was similar to the velocity of background drifters, which suggests that the anticyclones were advected by the background flow in which they were embedded. This implies that there is not a typical speed of eddies translating through the Caribbean. Instead, the speed of an eddy can vary significantly depending on its route, faster in the main Caribbean Current jet, slower in the regions outside of fast currents, especially slow just southwest of Cuba.

9. Conclusions

The new drifter data provide an improved picture of the distribution of Caribbean eddies and their characteristics. Coupled with the detailed mean current field, the observations of eddies suggest where and how they might have been formed. However, Caribbean eddies remain poorly known because of so few in situ observations, especially subsurface ones. Further study of the Caribbean anticyclones and cyclones is needed to determine their physical structure and water mass properties and to evaluate their importance to the general circulation. The anticyclones' water properties need to be compared to those of NBC rings in order to help clarify the origin of the anticyclones.

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