The Influence of Loop Current Perturbations on the Formation and Evolution of Tortugas Eddies in the Southern Straits of Florida

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The influence of Loop Current perturbations on the formation and evolution of Tortugas eddies in the southern Straits of Florida

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Abstract. Large cyclonic eddies on the northern edge of the Florida Current are the dominant mesoscale features within the southern Straits of Florida. The most prominent of these features is a quasi-stationary eddy that forms near the Dry Tortugas. Our observations, compiled from 3 years of advanced very high resolution radiometer measurements in the Straits of Florida and Gulf of Mexico, demonstrate a strong relationship between the generation of anticyclonic rings from the Gulf of Mexico Loop Current and the evolution of Tortugas eddies within the southern Straits of Florida. In six cases, Tortugas eddies evolve from cyclonic frontal eddies which form along the boundary of the Loop Current. The eddies remain stationary near the Dry Tortugas until they are impacted by an approaching Loop Current frontal eddy. The length of time an eddy spends near the Dry Tortugas is increased when the Loop Current sheds an anticyclonic ring. The involvement of a Loop Current frontal eddy in the ring-shedding process results in a delay in its, and hence the Tortugas eddy's, downstream propagation. Results suggest that the lifetime of a Tortugas eddy can be as long as 140 days when a ring-shedding event occurs, or as short as 50 days in the absence of any ring-shedding events. Upon entering the Straits of Florida, the Tortugas eddies are deformed by the narrowing topography and shrink to approximately 55% of their original size as they propagated downstream. The shrinking of these eddies is accompanied by an accelerated translation from 5 km/d in the western Straits of Florida to 16 km/d in the east.

1. Introduction

The Straits of Florida is a narrow channel between the Florida Peninsula and Cuba in which circulation is dominated by the Florida Current (Figure 1). The northern edge of the Florida Current, close to the Florida Keys, is host to an ensemble of cyclonic eddies ranging from 15 to 200 km in diameter and lasting from days to months [Lee, 1975; Lee and Mayer, 1977; Lee et al., 1992, 1995]. Large cyclonic eddies with diameters of 100 - 200 km have been identified as dominant features in the circulation within the southern Straits of Florida [Lee et al., 1992, 1995]. The eddies propagate along the northern boundary of the Florida Current (FC), nestled between the coast and a meander in the current. These features have been referred to as Tortugas gyres in the literature, after the Dry Tortugas region where they are believed to form (Figure 2). In this study we refer to the Tortugas gyres as Tortugas eddies to reflect their transient nature and upstream genesis. The eddies remain stationary for up to 100 days, and their longevity, coupled with other climatological factors in the Straits of Florida, maintains a larval retention zone near the Florida Keys National Marine Sanctuary [Lee et al., 1992; 1995]. The cyclonic circulation, between the coast and a swift boundary current, combined with prevailing downwelling favorable winds creates a region of enhanced surface convergence and may help to re-
hypotheses about their formation and evolution have been proposed. Our results, based primarily on satellite measurements, provide new information about the formation, evolution, and translation of these features. Specifically, the data suggest that the Tortugas eddies evolve from cyclonic frontal eddies which form along the edge of the Loop Current (LC) in the Gulf of Mexico.

Here we describe the evolution of six Tortugas eddies over a 3-year period spanning 1993 through 1996, using daily sea surface temperature fields derived from advanced very high resolution radiometer (AVHRR) satellite data. Satellite observations are combined with in situ observations from a moored acoustic Doppler current profiler near the 200 m isobath in the southern Straits of Florida (SSF). All six eddies were influenced by mesoscale variability associated with the surrounding current systems. Each of the Tortugas eddies evolved from LC cold perturbations like those described by earlier investigators [e.g., Vukovich et al., 1979]. The meander crest described by Lee et al. [1995], which is responsible for prompting the initial movement of the stationary Tortugas eddies into the SSF, is identified in all six cases as the leading edge of a new Tortugas eddy propagating into the SSF along the LC.

Following, we provide background information on the circulation of the Gulf of Mexico and SSF. In section 3,
we discuss the processing of the AVHRR and in situ measurements. In section 4, patterns of eddy evolution and eddy interactions within the Gulf of Mexico and Straits of Florida are identified and the kinematics of the eddies are quantified. Finally, a discussion of results follows in section 5.

2. Background

Flow in the eastern Gulf of Mexico and southern Straits of Florida is constrained by the straits' configuration and by two broad shallow shelves, the Campeche Bank and the west Florida Shelf (Figure 1). The Campeche Bank extends approximately 280 km north of the Yucatan Peninsula, bounding the flow entering the Gulf of Mexico through the Yucatan Channel. Likewise, the west Florida Shelf steers the flow along the west coast of Florida. Both shelves are clearly marked by steep escarpments on their seaward edge, plunging to depths beyond 3000 m in the central Gulf of Mexico. Sill depths in the Yucatan Channel, the channel connecting the Caribbean with the Gulf of Mexico, reach approximately 2000 m. The SSF is bounded on the north by the Florida Keys and on the south by the coast of Cuba. A shallow coral bank, Cay Sal Bank, is positioned where the channel and Florida coastline make a turn toward the north and is separated from the island of Cuba by the Nicholas Channel and from the Bahamas by the Santaren Channel. The width of the SSF decreases from 150 km at the western entrance to approximately 85 km near Cay Sal Bank, while water depths decrease from 2000 m at the western entrance to 800 m in the east.

Circulation in the eastern Gulf of Mexico is dominated by the LC, a portion of the Gulf Stream system that closes the subtropical gyre in the north Atlantic. Warm water flows from the Caribbean through the Yucatan Channel where it is called the Yucatan Current, loops anticyclonically through the northeastern Gulf of Mexico, and exits through the SSF where it becomes the FC. The LC penetrates into the northeastern Gulf of Mexico to varying degrees throughout the year, and occasionally an anticyclonic ring will separate from the current [Leipper, 1970; Maul, 1977; Muller-Karger et al., 1991; Sturges, 1992]. Typically, ring separation causes an abrupt southward retreat of the northern LC boundary and, consequently, the establishment of direct flow between the Yucatan Channel and the SSF [Leipper, 1970; Ichiye et al., 1973; Hurlburt and Thompson, 1980; Muller-Karger et al., 1991]. After a ring separates, the LC may take several months to reestablish its anticyclonic circulation in the northeastern Gulf of Mexico. However, occasionally, anticyclonic rings with diameters less than 250 km separate from the LC and do not produce a significant change in the northern position of the LC boundary [Vukovich, 1995]. In this scenario, the current still penetrates into the northeastern Gulf of Mexico, even after the ring has separated. The northward penetration of the LC has significant year-to-year variability with a mean period around 8.5 months [Sturges, 1992].

Early observational programs in the Gulf of Mexico were primarily focused on quantifying the cycle of northward penetration and anticyclonic ring shedding by the LC. However, observations revealed a wide range of smaller-scale features that were related to the large-scale processes. For instance, Leipper [1970] investigated current patterns in the northeastern Gulf of Mexico and found meanders and eddies located along the northern and eastern edges of the LC. This led to the first evidence that anticyclonic ring shedding may be preceded by the westward propagation of cyclonic eddies across the Yucatan Channel [Cochrane, 1972]. Several investigators have presented hydrographic data showing a closed cyclonic feature near the Dry Tortugas, which occasionally appears during ring separation in the LC [Nowlin and McLellan, 1967; Molinari, 1977]. The dynamic height maps of Ichiye et al. [1973] in the northeastern gulf show evidence of cyclonic eddies embedded in the edge of the LC just north of the Campeche Bank. No mention of the eddies is made by the authors, but they appear to have rough diameters of 50-100 km.

Curiously, although the Gulf of Mexico and SSF are geographically and dynamically connected by the LC, previous studies concerning the mesoscale variability associated with each have remained independent. The most comprehensive studies of LC frontal eddies (LCFEs) and perturbations took place in the late 1970s to early 1980s with the studies of Maul [1977], Vukovich et al. [1979], Paluszkiwicz and Atkinson [1983], and Vukovich and Maul [1985]. Vukovich and Maul [1985], combining more than 10 years of satellite infrared data and several years of coincident hydrographic measurements, identified large cold perturbations on the northern extreme of the LC that moved southward along the LC boundary, adjacent to the west Florida Shelf. These meanders eventually grew into stationary meanders with closed cyclonic streamlines and cold cores near the Dry Tortugas. Upon reaching the SSF, they were observed in one of two possible configurations: A large southwestward oriented protrusion of cold water near the Dry Tortugas [e.g., Maul et al., 1984] or a cold tongue, bounded to the west by the southward flowing LC and to the east by a ridge of warm water extending over the west Florida Shelf to as far north as 26°N [cf. Vukovich and Maul, 1985, Figure 2a]. The cold tongue and the cold meander events observed by Vukovich et al. [1979], Maul et al. [1984], and Vukovich and Maul [1985] always displayed the signatures of closed cyclonic circulation. Geostrophic estimates of velocities within the LCFEs exceeded 100 cm/s on the LC side of the features where horizontal density gradients were maximized, while velocities reached 20 cm/s over the west Florida Shelf. Diameters varied from 80 to 120 km, and
subsurface signatures extended to 1000 m [Vukovich and Maul, 1985]. Surprisingly, in 10 years of observations, the features were never observed moving into the SSF. Once the perturbations reached the Dry Tortugas, they either dissipated or grew westward, across the width of the LC. Vukovich and Maul [1985] postulated that dissipation of LCFEs may involve kinetic energy transfer to the mean flow, similar to the behavior of spin-off eddies described by Lee [1975] in the northern Straits of Florida. The lack of prior observations of such propagations may be an artifact due to aliasing of an imperfect sea surface temperature time series derived from early satellite images.

In a subsequent study, Vukovich [1988a] used a wave-staff technique on 5 years of infrared satellite data to quantify the boundary variations associated with the LCFEs. Perturbations along the northward flowing limb of the LC were 20-30 km near 25°N and grew to 90 km near 27°N, suggesting that perturbations generated at or entering through the Yucatan Channel grow as they propagate toward the northern section of the LC. The eddies observed by Maul et al. [1974] and Maul [1977], proposed to be generated by shear instabilities, and by Cochrane [1965], proposed to be a result of topographic vortex generation, were all of the order of 10-20 km. Two-layer model experiments generated cyclonic eddies downstream of the Yucatan Channel, east of the Campeche Bank [Hurlburt, 1986]. The model eddies were generated by baroclinic instabilities in the vicinity of the steep topography of Campeche Bank [Hurlburt, 1986].

To summarize, cyclonic eddies are common along the outer LC boundary, and observations have suggested that they may be important in the LC anticyclonic ring-shedding process. Model studies and observations suggest that these LCFEs form along the northward flowing branch of the LC and grow in an unstable manner as they propagate downstream. There are no prior published reports suggesting that these eddies propagate into the SSF upon reaching the Dry Tortugas.

Downstream in the SSF, flow variability is dominated by the cross-stream meandering of the FC axis which falls within a broad, 30- to 70-day band in the SSF [Lee et al., 1995]. Current oscillations at the shelf break, produced by the meandering of the FC, are associated with a myriad of cyclonic eddies found on the northern edge of the FC. The relatively long-period meanders in the FC axis are associated with the passage of large cyclonic eddies having diameters of 100-200 km. These features originate near the Dry Tortugas, near the southwest edge of the west Florida Shelf, and propagate eastward into the SSF. Chew [1974] reported large offshore shifts of the FC axis associated with fluctuations in the LC upstream. Using hydrographic data and drifter trajectories, he provided evidence for a large eddy-like feature nestled inshore of a meander in the FC. Later, Brooks and Niler [1975] reported the presence of cyclonic recirculation of FC water near Key West during a 1-month period of dropsonde measurements in 1972. Throughout this 1-month period, they observed that the axis of the FC remained approximately 80 km offshore while a persistent countercurrent was present nearshore.

Lee et al. [1992] were the first to launch an in-depth study of the circulation patterns within the SSF with emphasis placed on the recirculating features reported by previous investigators. Participants in the Southeast Florida and Caribbean Recruitment (SEFCAR) study began monitoring the circulation offshore of the Florida Keys in 1989 with moorings, hydrography, drifters, and infrared satellite data. Lee et al. [1992] reported observations of a cold, cyclonic gyre located over the Pourtales Terrace, thus named the Pourtales Gyre. They postulated that the gyre was caused by the offshore meandering in the FC in the vicinity of the Pourtales Terrace and, as a result, the enhanced cyclonic vorticity input to the system where the channel curves toward the north. Circulation velocities within the gyre ranged from 20 to 50 cm/s, and upwelling velocities in the center (2 m/d) caused a 50- to 75-m uplifting of colder waters onto the terrace. Subsequently, Lee et al. [1995] concluded that the Pourtales Gyre is a late stage in the evolution of larger features that form near the Dry Tortugas, Tortugas eddies.

Tortugas eddies have only been observed during periods when the LC penetrates into the northeastern Gulf of Mexico. Therefore it is anticipated that the life cycle of Tortugas eddies is affected by the variability associated with anticyclonic ring shedding by the LC. Lee et al. [1995] proposed that Tortugas eddies are formed when the LC, flowing south along the west Florida Shelf, overshoots the entrance to the Straits of Florida before turning cyclonically into the channel. During the period following the separation of an anticyclonic LC ring, when the northern boundary of the LC has retreated toward the south, Lee et al. [1995] did not observe any Tortugas eddies within the SSF. They concluded that the orientation of the LC entering the SSF the meanders in the FC axis, and the curvature of the topography at the western entrance to the SSF, contribute to the generation of Tortugas eddies near the Dry Tortugas. Lee et al. [1995] suggested that the LCFEs observed by Vukovich and Maul [1985] may provide an additional source of cyclonic vorticity to the eddies near the Dry Tortugas; however, no direct evidence of this process was presented. The Tortugas eddies observed by Lee et al. [1995] were elliptical with alongshore diameters reaching 180 km and cross-shore lengths reaching 100 km. The eddies persisted near the Dry Tortugas for approximately 100 days until an approaching meander crest in the LC prompted a 5 km/d (6 cm/s) translation downstream [Lee et al., 1995]. The convergence of flow near Cay Sal Bank typically sheared them apart [Lee et al., 1995].
3. Data Sources

The primary data source for this study is sea surface temperature (SST) observations derived from the advanced very high resolution radiometer, an infrared radiometer flown on National Oceanic and Atmospheric Administration (NOAA) polar-orbiting satellites. Infrared satellite observations have enhanced our understanding of oceanic systems by providing synoptic-scale pictures of SST patterns which are the signatures of mesoscale oceanic features. A full description of the algorithms used to calculate SST from infrared data is given by McClain et al. [1985]. Difficulties arise when the atmosphere is cloudy or contains high concentrations of water vapor as the infrared signal emitted by the sea surface is attenuated by atmospheric absorption [May et al., 1993]. In the SSF and the Gulf of Mexico, the sea surface becomes isothermal in the summer due to increased heating [May et al., 1993]. This causes difficulties in detecting gradients in SST and renders AVHRR data less useful during summer months (typically June through September [Müller-Karger et al., 1991]).

Infrared observations were collected for the period July 1993 through July 1996. The measurements encompass the area 79°W to 84°W and 22.75°N to 27.75°N at approximately 1 km resolution (Figure 2). As this study progressed, it was evident that information about the circulation in the Gulf of Mexico was essential to understanding the evolution of Tortugas eddies in the SSF. Frontal analysis maps produced by NOAA analysts for the Gulf of Mexico and Straits of Florida were obtained for the period July 1993 through June 1995. The charts identify dominant fronts and features from composites of AVHRR data and are used to provide information about the circulation in the Gulf of Mexico. AVHRR measurements collected by the University of South Florida for the Gulf of Mexico are used to identify fronts and features during July 1995 through July 1996.

In order to enhance the existing gradients in the SST fields, the data were subjected to a series of processing steps. First, clouds were identified and flagged using a combination of spatial homogeneity tests and SST thresholds. Second, the images were examined for partial coverage resulting from being on the edge of the scan of the satellite and for distortion during satellite passes with wide scan angles. The polar-orbiting satellites provided up to two passes per day, per satellite. During the study period there were at least two operational satellites at all times, providing up to four passes per day. With a few exceptions, during most summer months (June - September) Tortugas eddies were undetectable in the SST observations. The final processed data included 1898 images, corresponding to wintertime observations between the months of October and May, which were used to identify and track oceanic features such as Tortugas eddies.

The SST observations were used to locate the FC front and the LC front and to track the position, size, and shape of cyclonic eddies flanking these currents. Errors in derived SST values vary regionally but have been estimated at 0.6°C [McClain et al., 1985]. This study emphasizes pattern recognition in SST fields rather than the quantitative use of absolute SST values, and the AVHRR is highly sensitive to relative differences in SST. A frontal position, identified with AVHRR measurements, is based on temperature differences in the upper few millimeters of the ocean surface, whereas the same frontal position identified with hydrography is based on horizontal temperature differences deeper in the water column. Paluszczewicz and Atkinson [1983] found a 3-to 15-km disagreement between frontal positions identified with AVHRR data and those identified using hydrographic data for the LC.

Participants in the SEFCAR program (1989-1995) maintained current meter and acoustic Doppler current profiler (ADCP) moorings at several locations along the shelf, in addition to conducting hydrographic surveys in the SSF. All the current meter moorings were deployed at or shoreward of the 30-m isobath. As a result, the velocity measurements represent a combined response to forcing mechanisms on a variety of timescales. This makes it difficult to isolate the variability associated with the passage of Tortugas eddies from that associated with wind events and tides. SEFCAR also maintained a bottom-mounted ADCP mooring near Looe Key Reef that was positioned in deeper water, near the 150-m isobath (Figure 2). Variability at this site is dominated by large onshore–offshore shifts in the FC axis due to the passage of Tortugas eddies.

4. Results

An eddy is defined in the SST observations by a cooler water mass embedded in the northern edge of the warmer FC (Plate 1). When a Tortugas eddy is present, the FC meanders offshore to the southwest of the eddy and returns to hug the coastline to the east of the eddy. Often, streamers of warm water from the FC are pulled around the northern edge of the eddy, clearly tracing the cyclonic circulation within the feature. Therefore large changes in the position of the FC front are good indicators of the passage of a Tortugas eddy. Vukovich and Maul [1985] and Vukovich [1988a,b] monitored the evolution of LCFEs by quantifying perturbations along the boundary of the LC, and we employ a similar method to monitor the evolution of Tortugas eddies. A coast-following coordinate system was chosen with 17 wave staffs oriented perpendicular to the coastline in the SSF (Figure 2). The location of the northern edge of the FC front was recorded, whenever detectable, along each staff in the coordinate system for each SST snapshot. The front was identified by visually locating the maximum gradient in temperature along a staff. The time series of FC positions
Plate 1. Sea surface temperature (SST) for March 23, 1995, derived from advanced very high resolution radiometer (AVHRR) measurements. Cooler temperatures are represented by shades of blue and green, while warmer temperatures are represented by shades of oranges and reds, as depicted by the color scale. Clouds in the domain are represented by gray patches. A Tortugas eddy is located near 83°W, as evidenced by the cooler (green) surface waters north of the meander in the warmer (orange) Florida Current (FC). Streamers of warm FC water are advected cyclonically into the interior of the eddy.

Along each staff were used to derive various quantities that describe the first-order characteristics of the eddies as they propagated through the SSF. These quantities included translation speed, along-channel and cross-channel sizes, and eddy frequency and duration. Limitations exist due to the spatial and temporal discontinuities inherent in the SST fields due to cloud cover and undetectable gradients during summer months. Examination of the entire 3-year record of SST fields revealed the evolution of 11 Tortugas eddies. However, the detailed evolution of only six of these eddies is described here. The remaining five eddies were not examined, as the quality of the data was not consistently clear enough in order to detail their evolution. Table 1 shows the time frame in which each of the six eddies discussed herein were observed in the SSF. For convenience, we refer to specific eddies in the text according to the eddy number assigned in the first column of Table 1.

All six of the Tortugas eddies that were tracked using the SST observations remained stationary near the entrance to the SSF until they were impacted by a LCFE. However, two distinct circulation patterns were recurrent in the Gulf of Mexico, which had an effect on the continued evolution of the Tortugas eddies. Each mode involved a different phase in the anticyclonic ring-shedding cycle by the LC and is summarized by the schematic illustration in Figure 3. The first begins with a stationary Tortugas eddy near the Dry Tortugas. In
In the following sections we describe both modes in more detail as they correspond to the continual evolution of the six eddies identified in the SST observations. The second mode involves the shedding of a small anticyclonic ring by the LC. Here, the LC previously responsible for forcing the Tortugas eddy into the SSF never reaches the Dry Tortugas. Instead, the propagation of the LC is slowed due to the separation of an anticyclonic ring from the LC. It is important to note that the ring is sufficiently small to prevent a large southward displacement of the LC boundary. Therefore the stationary Tortugas eddy survives the ring separation, supported by the cyclonic flow curvature at the entrance to the SSF. In this scenario, the Tortugas eddy remains near the Dry Tortugas until a second LCFE approaches along the LC boundary. This LCFE forces the Tortugas eddy into the SSF where, like the first case, it translates downstream, gradually shrinking in size as it enters the narrow channel.

In the following sections we describe both modes in more detail as they correspond to the continual evolution of the six eddies identified in the SST observations. For convenience, eddies that were observed during mode 1 circulation conditions are referred to as mode 1 eddies while all others are called mode 2 eddies. A third circulation pattern has been identified in previous observations in which a large anticyclonic ring separates from the LC, causing the LC to retreat toward the Yucatan Channel [Vukovich, 1988a]. The subsequent absence of the Loop Current inhibits the formation of a new Tortugas eddy [Lee et al., 1995]. Each of the anticyclonic LC rings that was shed during the 3-year AVHRR measurement period was relatively small. This case will not be discussed here, as it was not observed in these SST observations.

### 4.1. Mode 1

Four of the six Tortugas eddies observed in this study are classified as mode 1 eddies: eddies 1, 2, 4, and 5 (Table 1). The satellite analysis charts produced by NOAA analysts have been redrawn to depict the position of the LC and FC fronts (Figure 4a). Figure 4a contains weekly snapshots spanning the period January 20 through April 21, 1994. Eddy 1 was located near the Dry Tortugas on January 20, the first panel in Figure 4a. The Tortugas eddy is defined on its seaward side by the offshore meander in the LC as it enters the SSF. Filaments of FC water advected westward, along the north side of the eddy, are evidence of the cyclonic circulation within the feature. This effect is well illustrated on February 10, 1994. Here a filament of FC water has been cyclonically wrapped into the core of the eddy. Eddy 1 remained stationary near the Dry Tortugas until mid-February. At this time, a LCFE of comparable size approached from the north and forced the Tortugas eddy into the SSF. As eddy 1 entered the SSF, it began to shrink, as indicated by the decreasing meander amplitude in the FC. Meanwhile, the LCF replaced eddy 1 near the Dry Tortugas to become eddy 2 (Table 1). The evolution of eddies 4 and 5 was similar to that of eddy 1. The LCFE that displaced eddy 4 into the SSF became stationary eddy 5. Similarly, a LCFE replaced eddy 5 (data not shown).

Eddy 2 was influenced by mode 1 circulation patterns throughout most of its lifetime. Eddy 2 initially appeared as a LCFE, forcing eddy 1 into the SSF and remaining stationary near the Dry Tortugas on February 24, 1994 (Figure 4a). On March 3, a LCFE was visible on the northern limb of the LC, and by March 31 it had begun to push eddy 2 into the SSF. However, after eddy 2 began its translation, the LC bent westward and the meander surrounding the LCFE amplified across the neck of the LC. Simultaneously (April 7), a tongue of warm water formed over the west Florida Shelf in a configuration similar to that described by

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### Table 1. Time frames for Tortugas Eddies Observed in the Straits of Florida as Inferred From Advanced Very High Resolution Radiometer Data

<table>
<thead>
<tr>
<th>Eddy</th>
<th>Mode</th>
<th>First detected</th>
<th>First Movement</th>
<th>Stationary Time, days</th>
<th>Last Detected</th>
<th>Total Duration, days</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>Jan. 11, 1994</td>
<td>Feb. 6, 1994</td>
<td>27</td>
<td>March 18, 1994</td>
<td>67</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>March 3, 1994</td>
<td>March 15, 1994</td>
<td>12</td>
<td>April 24, 1994</td>
<td>53</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>Nov. 8, 1995</td>
<td>Nov. 28, 1995</td>
<td>20</td>
<td>Jan. 9, 1996</td>
<td>63</td>
</tr>
</tbody>
</table>

The quantities reported for each eddy are representative of (1) the evolutionary mode, described in section 4; (2) the date when each eddy was detected near the Dry Tortugas; (3) the date of first movement into the southern Straits of Florida (SSF); (4) the total time that each eddy remained stationary near the Dry Tortugas; (5) the date when each Tortugas eddy was last detected near Cay Sal Bank; and (6) the eddy's total residence time in the SSF.
Figure 3. Schematics of the two circulation patterns common in the AVHRR observations. Lines drawn are representative of the position of the Loop Current (LC) and Florida Current (FC). The positions of cyclonic Loop Current frontal eddies (LCFEs), Tortugas eddies, and anticyclonic rings are labeled.

Vukovich and Maul [1985]. In this flow configuration, part of the southward flowing LC recirculates around the LCFE over the west Florida Shelf while the remainder of the flow is directed into the SSF [Vukovich and Maul, 1985]. The studies of Vukovich and Maul [1985] showed that this cold-tongue flow configuration often leads to anticyclonic ring separation. By this time of the year, the sea surface had become isothermal, and it is unclear from the SST fields whether a ring-shedding event ensued. However, satellite altimeter data suggest that an anticyclone formed approximately 2 weeks later (data not shown).

Frontal tracings were generated from the high-resolution SST observations within the SSF. The tracings depict the location of the high SST gradients associated with the position of the FC front. The line drawings depict the gross position of the FC front as well as smaller-scale perturbations along its boundary. A sample of the frontal charts is presented for eddy 1 to illustrate the evolution of mode 1 eddies within the SSF (Figure 4b). On February 7, eddy 1 was positioned near the Dry Tortugas and the FC flowed close to the northern coast of Cuba. Finger-like intrusions are present in the frontal tracing, indicative of the cyclonic circulation in the eddy. As the eddy began to translate downstream, it shrank considerably until it reached the northward bend in the SSF. There was no recognizable signature of eddy 1 in the surface temperature by March 22, indicating that the feature had been sheared apart within the narrowing channel.
Figure 4a. Frontal tracings redrawn from National Oceanic and Atmospheric Administration analyses for the period January 20, 1994 through April 21, 1994. Tracings depict the location of the high SST gradients associated with the position of the LC and FC.

The detailed evolution of eddy 2 is illustrated in Figure 5. On April 5, 1994, eddy 2 began propagating into the SSF. The meander crest that prompted its movement extended well to the north of the Florida Keys, and by April 13 a sharp corner (highlighted with an arrow in Figure 5) had formed in the frontal boundary. The location of the sharp corner in the frontal boundary overlays similarly shaped topography near the southwest corner of the west Florida Shelf (Figure 1). It is possible that because the meander crest was trapped over the west Florida Shelf in the form of a warm tongue, the Tortugas eddy was unable to translate coherently into the SSF and the direct, swift flow of the FC dissipated the eddy through shear stresses.
4.2. Mode 2

Eddies 3 and 6 were mode 2 eddies. The frontal analyses redrawn in Figure 6a illustrate the evolution of eddy 3. On January 24, 1995, eddy 3 was located near the Dry Tortugas. The axis of the eddy was oriented from northeast to southwest, as indicated by the large meander in the LC front. This configuration resembles the large southwestward oriented protrusion of cold water described by Vukovich and Maul [1985], which is frequently observed near the Dry Tortugas. By February 9, a LCFE was positioned along the northern limb of the LC, which was tilted toward the west away from the west Florida Shelf (Figure 6a). Meanwhile, eddy 3 remained near the Dry Tortugas, its size and shape continually changing due to the passage of smaller frontal eddies. It is difficult to determine from the surface temperature signature whether these smaller eddies were
Figure 6a. As in Figure 4a, but for the period January 24, 1995, through May 25, 1995. The position of the cyclonic LCFE, discussed in text, is labeled.

propagating around the periphery of the Tortugas eddy or whether the smaller eddies were coalescing with the larger eddy, resulting in the formation of filaments along the edges of the larger vortex. The overall effect was to alter the size and shape of the Tortugas eddy but not to prompt downstream translation. By February 23, the LCFE had propagated approximately halfway down the southward flowing limb of the LC. However, instead of continuing downstream, it began to enlarge westward, slicing across the width of the LC. By March 23, 1995, the surface signature of an anticyclonic ring appeared, indicating that it had separated from the LC. The filaments that appear along the northwest edge of the anticyclonic ring suggest that the smaller LCFE may
be orbiting the larger anticyclone. A similar cycle of deformation and filament formation has been observed in Gulf Stream rings [Hooker and Brown, 1994]. It is important to note that the anticyclonic LC ring was relatively small, approximately 250 km in diameter, and therefore its separation did not cause a complete southward retreat of the LC. The northern boundary of the LC was still located north of 25°N, thereby preserving eddy 3 throughout the ring-shedding process. The separated ring appears to prevent subsequent LCFEs from translating into the Dry Tortugas region and forcing eddy 3 into the SSF. It is possible that the LCFEs were unable to survive the cyclonic shear region maintained between the lingering anticyclone and the LC to the south. As a result, the residence time of eddy 3 near the Dry Tortugas approached 90 days. On April 13, the anticyclone appeared to partially reattach itself to the LC, and a week later a smaller ring separated from the current. By April 27, there was evidence that eddy 3 had propagated into the SSF. By the end of the sequence, a large warm tongue of LC water extended over the west Florida Shelf similar to the configuration observed by Vukovich and Maul [1985].

Similar frontal tracings were used to investigate the evolution of eddy 6 (Figure 6b). On January 17, 1996, eddy 6 forced eddy 5 into the SSF and remained near the Dry Tortugas. By January 27, a LCFE appeared along the northern boundary of the LC while a second LCFE followed close behind. Twenty days later, the larger perturbation in the northern LC boundary suggests that the two LCFEs had coalesced in the north. Meanwhile, a large LCFE had developed near the Yucatan Channel (February 16) and begun to propagate downstream along the northward flowing limb of the LC. With the convergence of these two features, a small anticyclonic ring separated from the LC. As in the above scenario, the anticyclonic ring was sufficiently small to prevent a significant southward shift in the LC boundary, and
eddy 6 was preserved throughout the ring-shedding process. Eventually, by May 27, a LCFE approached from the north and forced eddy 6 into the SSF. One notable characteristic of the mode 2 eddies was their long residence time near the Dry Tortugas, during which time the size and shape of the eddies changed dramatically. Once eddy 3 was forced into the SSF, it took only 2 weeks to reach Cay Sal Bank. Similarly, eddy 6 remained stationary for 121 days compared with its 19-day propagation through the SSF.

4.3. Kinematic comparisons

Changes in the size, shape, and speed of the Tortugas eddies were monitored using a time series of frontal positions recorded along each wave staff from the high-resolution SST observations in the SSF (Figure 2). Changes in the spatial scales of the eddies were estimated by tracking the along-channel and cross-channel sizes as they evolved (Figure 7). The cross-channel diameter of the eddies, oriented perpendicular to the coastline, was defined by the offshore meander in the FC frontal boundary. Paluszkiewicz and Atkinson [1983] found a 5-to 15-km disagreement between LC frontal positions identified using AVHRR data and those identified from hydrographic data. Halliwell and Mooers [1979] conclude that the position of the Gulf Stream could be determined to within 5 km using AVHRR data under optimum conditions. The error for the cross-
channel dimension of the eddies here is estimated at ±5 km. Following a method similar to Vukovich [1988b], the area between the FC meander and the coastline was calculated and, assuming the Tortugas eddy is elliptical in shape [Lee et al., 1992, 1995], the along-channel dimension of the eddy was computed. The boundaries over which to integrate the frontal curve were identified by the inflection points in the FC front upstream and downstream of the eddy. The error associated with this choice, coupled with uncertainties in the frontal digitization process, produces a combined error of approximately 15% in our along-channel calculations.

The changes in the cross–channel size of all six Tortugas eddies are remarkably similar (Figure 7). The cross–channel diameter of all six eddies decreases exponentially from 200 km near the entrance of the SSF to approximately 50 km near Cay Sal Bank. The along-channel dimensions of the eddies are not as predictable; however, some salient characteristics are evident in the evolution of the six eddies. The most dominant characteristic is the increase in along–channel size over the first six staffs, followed by a gradual decrease through the remainder of the SSF. On average, eddies entering the SSF had a cross–channel width of approximately 200 km and an along–channel length of approximately 115 km (Figure 7 and Figure 8). These dimensions are comparable to those reported by Vukovich [1988b] who found that as the LCFEs approached the Dry Tortugas, their along–stream to cross–stream size ratio inverted. Once the eddies enter the SSF, this ratio is inverted again due to the narrowing of the channel so that the along–channel dimensions are larger. The width of the SSF narrows considerably beginning around 83°W (staffs 4 through 8; Figure 2). In this portion of the channel, the large volume of the FC constricts the cross–channel size of the eddies. The average total area of the eddies is greatest near the entrance of the SSF, immediately after the axis–length inversion has taken place (Figure 8). By the time the eddies reach the narrowest portion of the SSF (north of Cay Sal Bank, near staff 14; Figure 2), their dimensions have decreased to approximately 170 km and 80 km in the along–channel and cross–channel directions, respectively, about 55% of their original size (Figures 7 and 8). The steady decrease in average eddy area at the surface implies that either the eddies are continually losing mass to the FC as they propagate downstream or that they spin faster and deepen. Observations by Lee et al. [1995] did not show an increase in swirl velocity as the features propagate downstream. If we assume that the eddies are cylindrical and penetrate to a depth of 300 m and that they propagate through the SSF in 38 days (the average propagation time for mode 1 eddies), then the effective rate of fluid lost by the eddies as they propagate through the SSF is approximately 0.7 Sv. 

The eddies experienced changes in their translation speed coinciding with the changes in eddy shape and size. Translation speed, defined as the time it takes for the center of a Tortugas eddy to advance from one staff to another, was estimated for each of the eddies as they propagated through the SSF. In order to avoid spuriously high velocity estimates due to changes in the size or shape of the features, velocities were only calculated between staffs separated by at least 55 km (i.e., skipping at least one staff). In this way, small deformations in the shape of a slowly moving eddy had minimal effect on translation calculations. Figure 9 shows the translation speed of eddies grouped by mode (Table 1), with error bars representing an estimated 10% uncertainty in the calculations. Staff 8 arbitrarily separates the western SSF from the eastern SSF (see vertical line in Figure 9). Velocity curves are incomplete for some of the eddies due to intermittent cloud cover. Results indicate that translation speeds increased as all six of the Tortugas eddies propagated into the middle SSF. Their maximum downstream speed coincided with the maximum decrease in eddy area, suggesting that each eddy accelerated while shrinking within the narrowing channel and had greater interaction with the FC. The mode
eddy speeds range from 5 km/d in the western SSF to 16 km/d in the eastern SSF. Eddy 2 stopped translating by the time it reached the middle SSF due to the warm-tongue formation over the west Florida Shelf. However, its translation speed was steadily increasing as it entered the western SSF. Mode 2 eddy speeds range from 2 to 12 km/d (Figure 9b). By the time the Tortugas eddies reached the middle SSF (defined by staff 8), all the eddies had similar translation speeds. However, eddy 3 (Figure 9b) had significantly slower propagation speeds in the western SSF compared with the mode 1 eddies. This difference may be attributed to the difference in size between eddy 3 and the mode 1 eddies. In the western SSF, eddy 3 is as much as 70% larger than the other eddies (Figure 7). However, it is likely that these differences in translation speeds are not statistically significant. The differences between the translation speed of eddy 3 in the western SSF and those calculated for eddies 1 and 2 are not greater than the differences in speed among mode 1 eddies. The important result is that all six of the eddies appear to accelerate through the middle SSF. Lee et al.’s [1995] estimate of 5 km/d is comparable to translation speeds observed in the western SSF; however, they did not report any downstream acceleration in their observations.

The most dominant correlation between the circulation patterns within the Gulf of Mexico and eddy kinematics is found in the longevity of the features. The lifetimes of each of the six Tortugas eddies are presented in Figure 10. Tortugas eddies 1, 4, and 5 were all mode 1 eddies and had residence times in the SSF of approximately 50-65 days. Through most of its life, eddy 2 behaved like a mode 1 eddy, and its life span, 53 days, reflects this similarity. Tortugas eddies 3 and 6, both mode 2 eddies, had much longer residence times of 105-140 days. This analysis seems to suggest that mode 1 eddies tend to take much longer to propagate downstream, approximately 30-40 days, than the mode 2 eddies which pass through the SSF in approximately 15-20 days. However, both of the mode 2 eddies were tracked into late spring when temperatures within the SSF had become isothermal and when feature identification became increasingly difficult. Therefore it is likely that the date of last detection underestimates their total lifespan when compared with other eddies that were observed during the fall and winter months.

This analysis is aliased due to the limitations of using the AVHRR sensor in this region during the warmer summer months. Satellite-derived ocean color measurements would probably be helpful in monitoring these eddies during summer months, as phytoplankton can...
Figure 11. Current velocities at 25m, 50m and 100m depth bins recorded by an upward looking 300-kHz ADCP moored at 150m near Looe Reef (see Figure 2). The velocity records have been 40-hour low-pass filtered to remove the high-frequency variability associated with tides. Current vectors have been rotated to align with the local isobaths so that vectors pointing toward the top indicate eastward flow. Shaded bars highlight the period when eddy 1 and eddy 2 passed over the mooring line.

serve as tracers of the circulation in the Gulf of Mexico [Muller-Karger et al., 1991]. However, there were no ocean color satellites operating during the period covered by this study. In situ observations were used to corroborate results inferred from the satellite data and to fill in the data gaps during summer months. Velocity measurements from a moored ADCP located at the 150-m isobath near Looe Reef overlap the SST observations from July 1993 through December 1994 (Figure 2 and Figure 11). Current vectors were rotated to align with the isobaths and filtered with a 40-hour low-pass filter to remove tidal signals. The passage of a Tortugas eddy is marked by significant current reversals throughout the water column that can last from 1 to 4 weeks. Westward flow reached 50 cm/s for several of the eddy events in the record. Shaded boxes (Figure 11) highlight the period when eddies 1 and 2 passed over the instrument. The passage of the eddies is suggested by the significant velocity reversals from dominantly eastward to westward velocities throughout the water column. The westward flow event that occurred in late January 1994 was caused by the passage of a Tortugas eddy that propagated through the SSF prior to the passage of eddy 1. This Tortugas eddy was present in the frontal maps on January 20, near the eastern boundary of the SSF (Figure 4a). There were 12 such events during the 17-month record or an average of about 10 events per year, although all of these Tortugas eddies could not be tracked using AVHRR observations due to the isothermal nature of SST during summer months. This velocity record was divided into winter (October - May) and summer (June - September) time series to correspond with the usable and unusable portions of the satellite observations. Variance-conserving spectra were computed for the two time series and compared (Figure 12). The spectra are similar, with the highest variability centered around 40 days. This suggests that conclusions derived from the wintertime SST fields are
applicable to the entire year and that there is no obvious seasonality in the eddy signals. The 40-day spectral peak appears to result from the passage of the Tortugas eddies. An average of 10 Tortugas eddies per year gives a fluctuation timescale of about 36 days and is the dominant mode of current variability at the site (Figure 11). This is consistent with the 30- to 70-day periods previously reported for the dominant current variability in the SSF [Lee et al., 1992, 1995].

5. Discussion

The lifetime of a Tortugas eddy may be controlled by several geographic and oceanographic factors. However, the most important factor appears to be the eddy’s relationship with the LC and its anticyclonic ring-shedding cycle. For instance, it appears from the SST observations that Tortugas eddies require the impact of an LCFE to initiate their movement into the SSF. Each eddy was forced into the SSF by an LCFE of comparable size which quickly replaced the displaced Tortugas eddy. In the absence of an LCFE, all six Tortugas eddies remained stationary near the Dry Tortugas. Mode 2 circulation patterns were characterized by the diversion of an approaching LCFE into the anticyclonic ring-shedding process. Maul et al. [1978] reported a 65-day period associated with LC perturbations, while Vukovich and Maul [1985] reported a 60- to 90-day time period from the generation of a detectable LCFE to identifiable anticyclonic ring separation. Assuming it takes 60-90 days for the anticyclonic ring-shedding process to complete, during which time a Tortugas eddy is present near the Dry Tortugas, and assuming it takes another 65 days for a new LCFE to propagate into position to interact with the Tortugas eddy, then the total stationary time of the original Tortugas eddy would be approximately 125-145 days. This is within the range of mode 2 eddy lifetimes. The lifetime of mode 1 eddies (Figure 10) is slightly shorter than the 65-day period associated with the evolution of the LCFEs as reported by Maul et al. [1978]. Mode 1 eddies were more common during this study period. On the basis of the residence times estimated for mode 1 eddies, ranging from 50-65 days (Figure 10), we could expect six to seven Tortugas eddies in the SSF per year. This is slightly less than the 10 eddy per year estimate from the ADCP data (Figure 11); however, it is difficult to isolate reversals in the velocity records that are caused purely by the passage of Tortugas eddies from the effects of relatively high frequency, submesoscale eddies [Shay, 1997; Graber and Limouzy-Paris, 1997].

An apparent inconsistency exists between the number of eddies we describe here and the number predicted by the velocity time series measured by the ADCP and inferred from the residence times of the eddies observed in this and previous studies. We have argued based on reversals in the velocity record that 12 eddies propagated through the SSF in a period of 17 months. This suggests that 17 Tortugas eddies should have propagated through the SSF during the 24 months of winter AVHRR observations. Similarly, independent estimates based on our AVHRR data and results from previous studies predict that between six and seven Tortugas eddies pass through the SSF in a given year. This implies that we should have observed approximately 13 mode 1 eddies or nine eddies if one third of those observed were mode 2 eddies. The number of eddies that we have actually described here is significantly less than the numbers predicted above. However, up to three additional eddies were identified in the SST fields prior to the appearance of eddy 1 in January 1994 and two eddies were identified prior to the appearance of eddy 3 in January 1995. These eddies were not described in detail here because the quality of the data between October and January was not consistently clear enough in order to detail their evolution. However, taking into account these additional eddies, the total number of eddies that we identified during the 24 months is 11. This number is consistent with the 9-13 eddies inferred from the AVHRR results. However, this number is still significantly smaller than the 17 eddies predicted by the ADCP velocity record. The passage of Tortugas eddies was identified in the velocity record by significant reversals from dominantly eastward to westward velocities throughout the water column. However, current fluctuations may also be caused by the passage of submesoscale frontal instabilities having diameters of 10 - 20 km which propagate through the SSF in timescales...
of days to weeks. These eddies would tend to cause smaller magnitude reversals that are confined to the upper 50–80 m in the water column [Shay, 1997]. It is possible that we have overestimated the number of eddies that propagated through the SSF during the 17-month deployment by including reversals forced by smaller frontal eddies.

Some puzzling questions remain. Foremost, what would cause a cyclonic LCFE to contribute to an anticyclonic ring-shedding event, rather than translating downstream into the SSF? LC anticyclonic ring shedding has been characterized by Hurlburt and Thompson [1982] as a cycle of northward penetration and westward bending of the LC, whereby the LC reaches an unstable configuration. Model results suggest that small cyclonic frontal eddies spin up through barotropic instability processes during the final stages of ring separation [Hurlburt and Thompson, 1982]. Model results and observations have also shown evidence of closed circulation in subsurface layers before surface signatures of a ring separation appear [Hurlburt and Thompson, 1982; Molinari, 1977]. Vukovich and Maul [1985] speculate that the cold features intensify through instability processes, thereby leading to the formation of an anticyclone that has closed circulation below the surface. They propose that the cold features then move westward in the shear zone between the ring and the LC to the south.

There is evidence both in model experiments and observations that LCFEs are continuously formed due to baroclinic instabilities near the steep topography of the Campeche Bank. Two-layer models generate LCFEs downstream of the Yucatan Channel, east of the Campeche Bank [Hurlburt, 1986]. The modeled eddies have comparable sizes and speeds to the LCFEs observed by other investigators. Vukovich [1988a] reported perturbations along the boundary of the northward flowing limb of the LC which grow from 20 to 90 km by the time they reach the northern boundary of the LC. The data from this study show that cyclonic LCFEs are found not only preceding a ring-shedding event but also during the entire extension process.

Figure 13 illustrates the changing orientation of the LC during the periods January 1994 through April 1994, January 1995 through June 1995, and November 1995 through May 1996. The dots indicate the northernmost position of the LC axis, as determined from the SST fields at various times during each clear image sequence. During the period January 1994 through April 1994, the northern LC boundary grew into the northern Gulf of Mexico and showed signs of westward bending (Figure 13a). During this time, eddies 1 and 2 propagated into the SSF. Recall that during April 1994, a warm tongue of LC water extended over the west Florida Shelf, hindering the coherent propagation of eddy 2. During the period January 1995 through June 1995, the LC boundary gradually extended northward and westward, followed by an immediate retreat to the southeast (Figure 13b). It was during this retreat to the southeast that an anticyclonic ring separated from the LC as indicated by the jagged line. Eddy 3 was positioned near the Dry Tortugas throughout this entire sequence. The LCFE upstream of eddy 3 reached the southward flowing limb of the LC during the northwest-
ward extension period and began to propagate westward across the LC. During the period November 1995 through May 1996, the LC boundary shifted northward and then bent westward (Figure 13c). This westward shift was immediately followed by a large eastward shift, during which time an anticyclone separated from the current. Eddies 4 and 5 were forced into the SSF during the stages preceding the large westward bending of the LC while eddy 6 remained stationary near the Dry Tortugas throughout the westward bending period. The subsequent eastward retreat of the LC coincided with the separation of a small anticyclonic ring from the LC.

Our results suggest that if the LC is in the unstable configuration defined by Hurlburt and Thompson [1982], bent westward away from the west Florida Shelf, and if a LCFE is present along the eastern edge of the LC, then that LCFE may be absorbed into the ring-shedding process. From the SST observations, it appears that the LCFE is locally strengthened, perhaps due to the instability mechanism proposed by Vukovich and Maul [1985]. In both of the cases presented here, the anticyclone that separated from the LC was relatively small, suggesting that the position of the LCFE when the current assumes an unstable configuration may help dictate the size of the anticyclone. The separation of a small anticyclone does not cause the total retreat of the LC to the south, thereby preserving the stationary Tortugas eddy. In the case of Tortugas eddy 2, the thermal contrast in SST was lost before we could tell what happened to the warm tongue configuration that formed near the Dry Tortugas. However, on the basis of the position of the LC and the ideas presented above, we might expect a large anticyclone to develop. Satellite altimetry observations confirm the formation of an anticyclone on May 15, 1994.

Mesoscale motion plays a crucial role in the recruitment of a larval community, as the hatched fish or lobster larvae may be retained in or advected away from favorable nursery grounds [Okubo, 1994]. The life span of a Tortugas eddy may dictate which larval species spend their planktonic stage in the Florida Keys region. For instance, slipper lobster (Scyllarus) and grouper (Serranidae) and snapper larvae (Lutjanidae) have planktonic stages that can last at least 1 month [Robertson, 1968; Leis, 1987]. Tortugas eddies have been observed in the middle SSF, stalled over the Pourtales Terrace for up to 1 month, and it has been proposed that these eddies may provide a local recruitment pathway for these species [Lee et al., 1992]. Model studies suggest that in the presence of a cyclonic eddy shoreward of a strong boundary current, winds blowing against the current induce unbalanced surface stress patterns [Rooth and Xie, 1992]. This situation may produce enhanced surface convergence in the region between the FC axis and a Tortugas eddy, thereby providing a means for surface water advected by the FC to be entrained into nearshore recirculations. Species having planktonic stages too long for local recruitment may be advected into the SSF from upstream sources in the Caribbean and recruited into the Florida Keys using the Tortugas eddies as a mechanism for transport out of the FC [Lee et al., 1992]. This may also be a mechanism for entrainment of red tide organisms into the Florida Keys waters.

Surprisingly, previous studies found no evidence that LCFEs become Tortugas eddies in six separate cases. In all cases, the departing Tortugas eddy was quickly replaced by a LCFE which subsequently remained stationary near the Dry Tortugas. It has been proposed that the longevity of stationary Tortugas eddies enables a longer advection pathway for those larval species that have longer planktonic stages [Lee, 1998]. These results suggest that the stationary period of a Tortugas eddy may vary widely, with mode 2 eddies remaining stationary for twice the amount of time that mode 1 eddies do. The mode 1 scenario was most common in these observations. This is to be expected in a larger sample if the evolutionary patterns of Tortugas eddies are truly determined by the separation period of anticyclonic rings by the LC. The period associated with ring separation by the Gulf of Mexico LC may vary from 6 to 25 months [Vukovich, 1988a; Sturges, 1992], whereas the evolution of LCFEs has been associated with a 65-day period in the spectrum of LC variability [Maul et al., 1978]. This would imply that the residence time of Tortugas eddies near the Dry Tortugas should approach 65 days a majority of the time while only occasionally exceeding 125 days. This variability in residence times could have profound implications for the successful recruitment of certain species into the SSF. On the basis of these results, the longest recruitment pathway would occur when a mode 1 eddy is propagating through the SSF while a mode 2 eddy is present near the Dry Tortugas. It is possible, however, that a larger sampling of Tortugas eddies might define other patterns of eddy evolution.

6. Conclusions

Observations compiled from 3 years of AVHRR data in the Straits of Florida and Gulf of Mexico were used to identify patterns in eddy evolution and relate them to the anticyclonic ring-shedding cycle by the Gulf of Mexico LC and to the evolution of LCFEs propagating along the LC boundary. These observations demonstrate a strong relationship between the generation of anticyclonic rings from the Gulf of Mexico LC and the evolution of Tortugas eddies within the SSF. Two common patterns in eddy evolution emerged from the observations of six separate Tortugas eddies: A Tortugas eddy is approached from upstream by a LCFE of comparable size and forced into the SSF by its impact or the southward propagation of an approaching LCFE is interrupted by the separation of a small anticyclonic ring from the LC. In the second mode, stationary Tortugas eddies must await impact by subsequent LCFEs before
they are able to propagate into the SSF. Observations suggest that LCFEs propagating along the boundary of the LC were detained by the ring-shedding process when the axis of the LC was undergoing northwestward spreading. A twofold increase in residence times was observed for Tortugas eddies that survived the separation of a small anticyclonic ring from the LC. The mode 1 Tortugas eddies were characterized by shorter residence times near the Dry Tortugas, typically 50-60 days, while mode 2 Tortugas eddies were characterized by longer residence times, typically 105-140 days. The absorption of the LCFE into the ring-shedding process increased the residence time of the Tortugas eddy and lengthened the retention timescale for larvae and pollutants near the Florida Keys National Marine Sanctuary.

The kinematics of the six Tortugas eddies were reasonably similar. The eddies were deformed upon entrance into the SSF due to the narrowing topography and continued to decrease in size as they propagated downstream. The shrinking of the eddies was accompanied by an accelerated translation from 5 km/d in the western SSF to 16 km/d in the eastern SSF. This acceleration was not reported in previous studies. The size of the eddies ranged from an average 200 km in the cross-channel direction and 115 km in the along-channel direction, near the entrance to the SSF, to 70 km and 165 km, respectively, near Cay Sal Bank. These dimensions are comparable to those observed in previous studies and correspond to a decrease in eddy area of approximately 55% between the Dry Tortugas and Cay Sal Bank. The steady decrease in average eddy area observed at the surface roughly corresponds to an effective fluid loss by the eddy of approximately 0.7 Sv.

By closely monitoring the evolution of several Tortugas eddies, we have demonstrated several new ideas. (1) Tortugas eddies may be the downstream expression of LCFEs. (2) A Tortugas eddy will remain stationary near the Dry Tortugas until it is impacted by a LCFE. (3) Because LCFEs are an integral part of the LC’s anticyclonic ring-shedding process, the longevity of a Tortugas eddy can be expected to vary in response to the LC’s ring-shedding cycle. Because Tortugas eddies have been identified as an important mechanism for the transport of larvae within the coastal environment surrounding the Florida Keys, this final point may be critical to the identification of recruitment pathways and retention timescales within the SSF.

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References
Cochrane, J. D., The Yucatan Current, annual report, project 266, Ref. 65-177, pp. 20-37, Texas A&M Univ., College Station, Tex., 1965.
Ichiiye, T., H. Kuo, and M. R. Carnes, Assessment of currents and hydrography of the eastern Gulf of Mexico, Control 601, Texas A&M Univ., College Station, Tex., 1973.
Maul, G. A., D. R. Norris, and W. R. Johnson, Satellite...


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