Evolution of the Tortugas Gyre and its Influence on Recruitment in the Florida Keys

Thomas N. Lee, M. E. Clarke, Elizabeth Williams,
Alina F. Szmant and Thomas Berger

SEDAR103-RD-20

1994

BULLETIN OF MARINE SCIENCE, 54(3): 621–646, 1994

EVOLUTION OF THE TORTUGAS GYRE AND ITS INFLUENCE ON RECRUITMENT IN THE FLORIDA KEYS

Thomas N. Lee, M. E. Clarke, Elizabeth Williams, Alina F. Szmant and Thomas Berger

ABSTRACT

Moored current measurements, satellite-tracked drifters, shipboard hydrography and a time sequence of satellite derived surface thermal images are used to show the formation and evolution of cold, cyclonic gyres coupled to large offshore meanders of the Florida Current in the southern Straits of Florida (SSF). Gyre formation is dependent upon the orientation of the Loop Current as it enters the SSF. With a well developed Loop Current the flow overshoots the entry to the SSF causing the formation of a cold recirculation off the Dry Tortugas, approximately 200 km in size, that persists over time scales of about 100 days. The demise of the gyre occurs as it moves to the east at about 5 $km \cdot d^{-1}$, reducing to half its original size off Big Pine and Marathon Keys and unobservable off the northern keys. Previously observed local gyres between Key West and Islamorada, FL (Lee et al., 1992) are identified as a latter stage in the downstream evolution of the gyres formed off the Tortugas. When the Loop Current is not developed, flow from the Yucatan Channel turns anticyclonically into the SSF, causing strong eastward flow over the slope off the Dry Tortugas and lower Florida Keys, and gyre formation does not occur. Gyre formation provides enhanced food supply, retention and shoreward transports for successful recruitment in the western and lower Florida Keys of locally spawned snapper and grouper larvae. A previously unknown potential retention area for larval invertebrates and fish on the southwest Florida shelf has been identified from a satellite tracked drifter trajectory, and a local lobster recruitment pathway combining advective influences from the Tortugas gyre, Loop Current and shelf circulation are proposed.

Recent observations of coastal water motions made in the lower Florida Keys to the Dry Tortugas are combined with measurements of the large-scale flow and temperature variability of the Florida Current (FC) to show the evolution of recirculating gyres on the northern side of the FC in the southern Straits of Florida (SSF). The occurrence of these gyres has significant implications for the recruitment of fish and lobster larvae into the Florida Keys, as well as the onshore transport of nearsurface contaminants that could occur in the case of an offshore oil spill in the eastern Gulf of Mexico or SSF. In a previous study we described a cold, cyclonic gyre that was observed over the Pourtales Terrace (Fig. 1) between Key Largo and Key West (Lee et al., 1992). This feature was named the "Pourtales Gyre" due to its observed coincidence with the Pourtales Terrace. Gyre formation over the terrace was explained as resulting from offshore meandering of the FC and enhanced curvature vorticity where the SSF curves toward the north. By combining recent current meter and hydrographic data from the coastal waters off the southwestern keys, taken as part of a NOAA supported study of South and East Florida Caribbean Recruitment (SEFCAR), together with offshore current meter and satellite thermal imagery, obtained through a Minerals Management Service (MMS) study conducted by Science Applications International Corp. (SAIC, 1992), we are able to show that the Pourtales Gyre is a later stage in the evolution of a large recirculation feature that is first formed off the Dry Tortugas, where the Loop Current turns abruptly to the east and enters the SSF (Fig. 1). The life history of this gyre is strongly connected to the major mode of variability of the FC in this region.

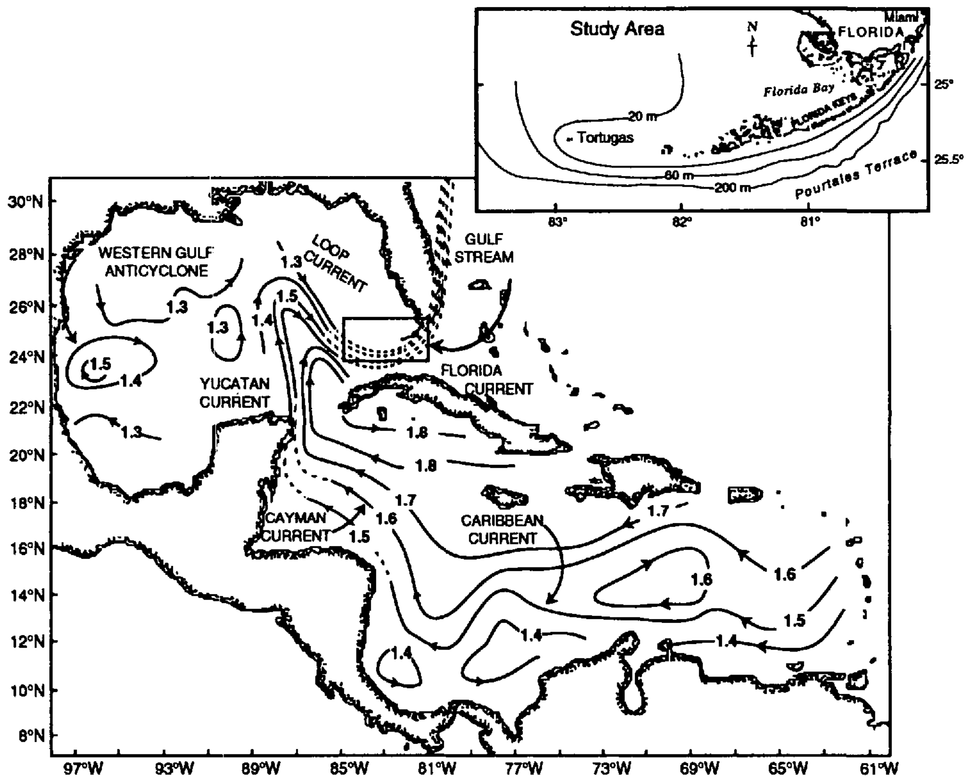

Figure 1. Location of study area and major current systems as determined from mean annual dynamical topography (dyn m) adapted from Molinari (1980: Fig. 2).

Background

The Straits of Florida is oriented in an east-west direction in the southern region below 25°N and turns cyclonically to a north-south orientation above 25°N (Fig. 1). A shallow coral bank, the Cay Sal Bank, is located in the center of the channel where the northward turn occurs and separates the Straits of Florida from the Santaren Channel. Water depths in the strait decrease from about 2,000 m at the westward entrance to less than 800 m in the northern straits.

The Straits of Florida acts as a conduit for the FC, which connects the flow out of the eastern Gulf of Mexico, the Loop Current, with the north Atlantic western boundary current, the Gulf Stream (Fig. 1). The upper layer waters of the FC with temperatures greater than 24°C are derived primarily from the South Atlantic (Schmitz and Richardson, 1991), and are transported across the equator and through the Caribbean by the combined influence of the North Brazil Current and the North Atlantic wind driven Sverdrup circulation.

A considerable background of information exists on FC variability in the northern straits, and on the Loop Current in the eastern Gulf of Mexico, but until recently, very little was known about the flow behavior in the SSF. Brooks and Niiler (1975) found the axis of the FC to be located about 80 km offshore of Key West during a 1-month period of dropsonde measurements in the summer of 1972, and a persistent counterflow occurred along the northern shore. They interpreted this counterflow as a cyclonic recirculation of the FC water. Chew (1974) also showed evidence in hydrographic and drifter data of a recirculation feature shoreward of a large offshore meander of the FC off the lower keys. Vukovich (1988) used satellite thermal imagery to conclude that a quasi-persistent cold perturbation exists off the Dry Tortugas, where the southward flowing Loop Current turns eastward into the SSF.

The above observations of flow variability are in marked contrast to the behavior of the FC in the northern straits and to the Loop Current. The current axis in the northern straits is located about 25 km offshore on the mean, no persistent counterflow is observed, and the dominant mode of variability is associated with northward advection of weekly-period meanders and frontal eddies, with cross-channel displacements of 5 to 10 km (Duing, 1975; Duing et al., 1977; Lee and Mayer, 1977; Brooks, 1979; Lee et al., 1985; Leaman et al., 1987; Johns and Schott, 1987; Schott et al., 1988). The Loop Current, on the other hand, displays large northward excursions into the eastern Gulf of Mexico and eddy shedding with mean periods ranging from 8.5 to 12 months (Maul, 1977; Sturges, 1992; Maul and Vukovich, 1993). Northward penetration of the Loop Current tends to be maximum in late summer and minimum in fall and early winter, similar to the annual cycle of FC transport, but with considerable year-to-year variability (Maul, 1977). Cyclonic frontal eddies, similar to those observed north of the Straits of Florida (Lee and Atkinson, 1983), are carried southward by the Loop Current along the seaward edge of the southwest Florida Shelf on 2 to 14 day time scales (Paluszkiewicz et al., 1983).

Recent year-long moored current records from the shelf edge in the Florida Keys, seasonal hydrographic surveys and ADCP profiles from the Pourtales Terrace reveal the structure of a cold, cylconic gyre that occurs over the terrace between Key Largo and Key West several times per year (Lee et al., 1992). Spatial dimensions of the gyre are on the order of 100 km in the alongshore direction and 40 km cross-shore. Circulation velocities range from 20 to 50 $cm \cdot s^{-1}$. Upwelling velocities in the center of the gyre are estimated at 2 $m \cdot d^{-1}$ and appear to cause a 50 to 75 m uplifting of cold, fresh waters onto the terrace from deeper strata of the FC. Indications are that the formation of the gyre is dependent on the onshore/offshore meandering of the FC and on the cylconic flow curvature induced by the northward curving channel.

Observations

A 1-year field study of the physical oceanography of the FC was undertaken by SAIC of Raleigh, N.C. with MMS support starting in November 1990. The study involved maintenance of a large moored current meter array, seasonal hydrographic and current profiling cruises, and analysis of remote thermal imagery obtained from the University of Miami/RSMAS Satellite Facility. The array consisted of moored current meters at two to four levels from about 100 m to near bottom, on four cross-channel transects (Fig. 2: transects A, B, C, D), as well as moored transects across the Northwest Providence Channel (E), Santaren Channel (F) and Old Bahama Channel (G). Details of the array design and full descriptions of all the data are included in the final report to MMS (SAIC, 1992). In this paper we are concerned only with variability in the SSF involving measurements from transects A, B and F. Transect A extends offshore of Marquesas Key to approximately the mid point in the channel, which is aligned in a east/west direction in this region. Transect B spans the FC, from inshore of the Pourtales Terrace to the Cal Sal Bank, and transect F is across the Santaren Channel. The SAIC study was coordinated with an ongoing study of the influence of recirculating gyres on recruitment of fish and lobster larvae into the Florida Keys (SEFCAR) conducted by the University of Miami/CIMAS with NOAA support (Lee et al., 1992). The physical oceanographic component of SEFCAR involved maintenance of coastal current meter moorings at the shelf edge (30 m isobath) on transects A and B and off the Dry Tortugas (DT), together with a bottom ADCP at the 200 m isobath off the Tortugas (Fig. 2, ADCP287), hydrographic surveys of gyre features off the Tortugas in early summer and release of ARGOS satellite-tracked near-surface drifters. There is a 7 month common time period between all moored measurements from April to November 1991. The SEFCAR moorings were continued till

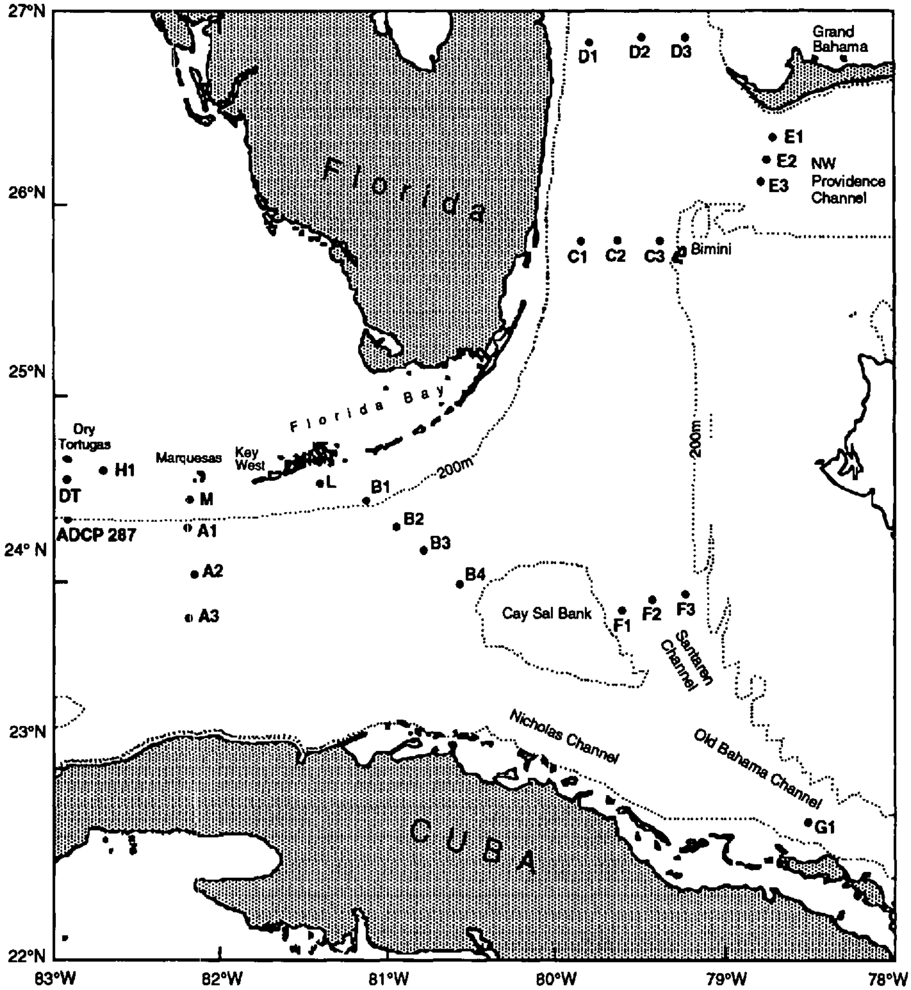

Figure 2. Current meter array, moorings A–H deployed by SAIC for period Nov. 90–Nov. 91, moorings DT, L and M deployed on the 30 m isobath and ADCP 287 deployed at 200 m as part of the SEFCAR Project for the period April 91–April 92.

mid April 1992. Nutrient levels and microzooplankton distributions were determined at different depths over the upper 200 m from 30-liter Niskin bottle samples at CTD stations during the hydrographic surveys. All time series data have been filtered with a 40-h low-pass Lanczos filter kernel to remove variance associated with tidal and inertial motions and form a low-frequency (subtidal) data set that is subsampled every 12 h.

Results

Low-frequency Current and Temperature Variability.—The horizontal distribution of low-frequency current and temperature variations in the upper 300 m from the SSF are shown in Figures 3a, b; 4a, b for a 1-year period (December 90 to December 91). Data at the 300 m level are shown for mooring sites deeper than this depth and at shallower sites the upper level records are used. Current and temperature fluctuations at these depths are used to represent the variability that occurs over the total water column, for flow events are for the most part barotropic

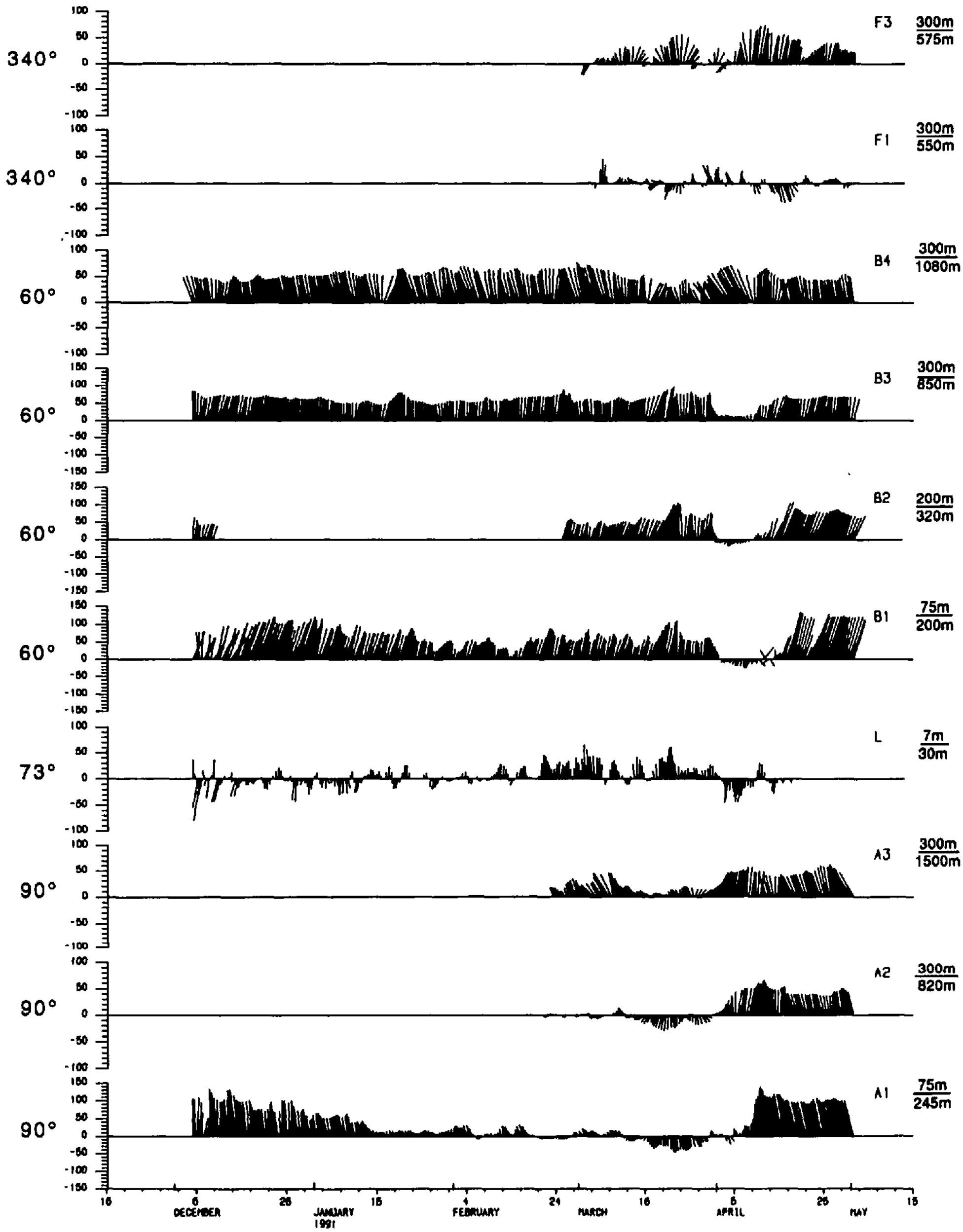

Figure 3a. Low-frequency current vectors rotated to align with local isobaths for the period Dec. 90–May 91. Mooring I.D., instrument depth and water depth given to the right, rotation angle given at the left, speeds are cm·s^{-1}.

and display highly coherent, in phase current and temperature variations over the vertical instrument separations. Sea surface thermal patterns from satellite AVHRR imagery were analyzed for the period December 90 to April 91. Surface thermal maps were derived from weekly composites of warmest pixels from the satellite imagery and are shown in Figures 5a–h, together with daily averaged

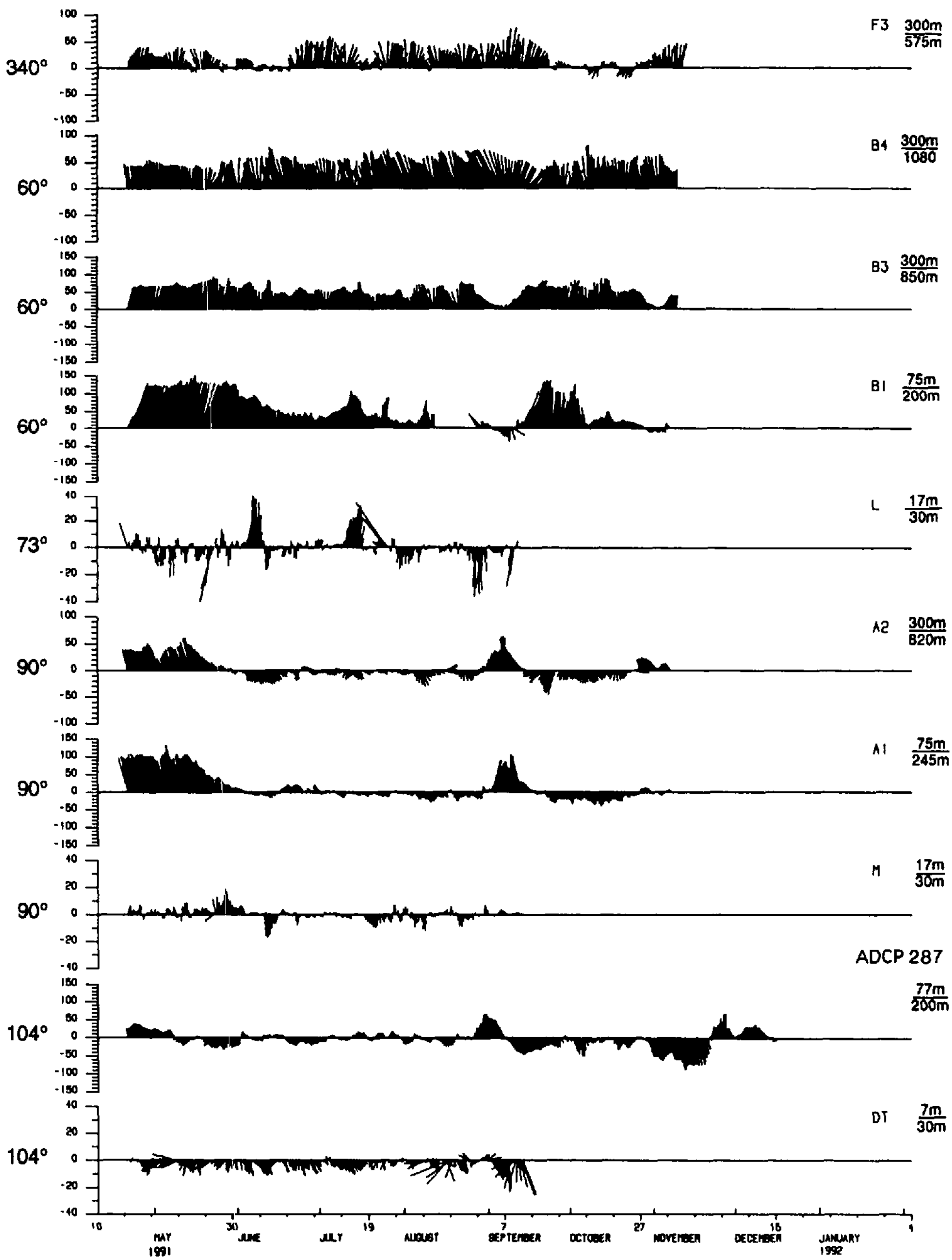

Figure 3b. Low-frequency current vectors rotated to align with local isobaths for the period May–Dec. 91. Mooring I.D., instrument depth and water depth given to the right, rotation angle given at the left, speeds are cm·s^{-1}.

currents computed from the upper level current meter records for the mid point of each composite week. In general, there is excellent agreement between the satellite derived surface temperature patterns and measured flow fields in the upper layer. Maximum current speeds tend to occur at maximum temperature gradients

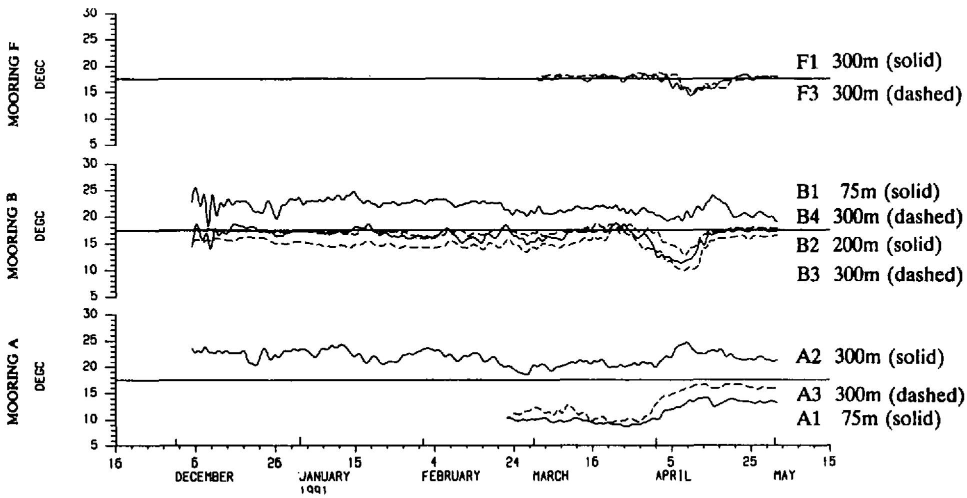

Figure 4a. Low-frequency temperature for the period Dec. 90–May 91. Mooring I.D. and instrument depth given to the right.

and in the warmest (red) waters. Also current directions are parallel to the temperature gradients as in a thermal wind balance i.e., warmer water to the right of the downstream vector.

DECEMBER 90–MAY 91. Viewed together, the current and temperature records and surface thermal patterns for December through April reveal the development of a large offshore meander of the FC in February and March that occurs near the western entrance to the SSF (Figs. 3a, 4a, 5). This meander is coupled to a cold, cyclonic circulation on the north side of the FC front near the Dry Tortugas. The development, evolution and eastward movement of these features appears to dominate the low-frequency variability in the SSF.

The FC front was located in an onshore position near transects A and B in

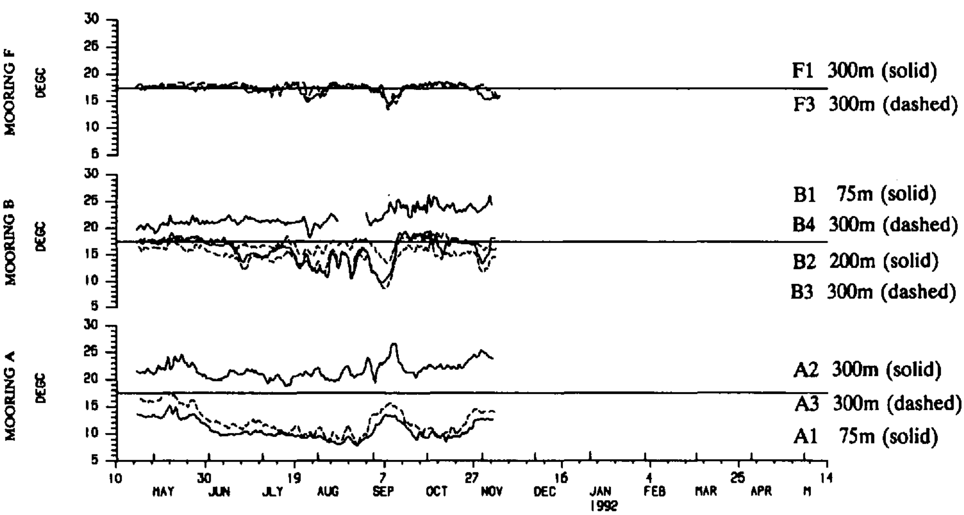

Figure 4b. Low-frequency temperature for the period May–Dec. 91. Mooring I.D. and instrument depth given to the right.

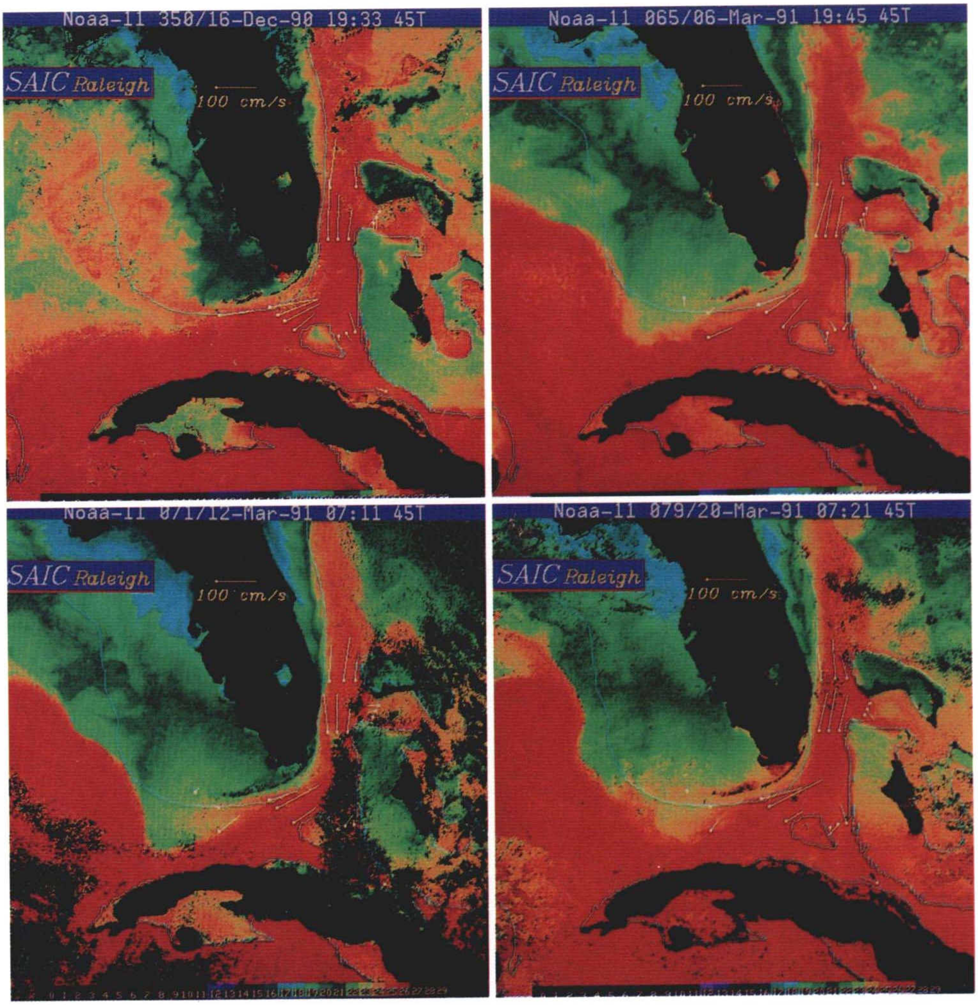

Figure 5. Surface thermal patterns derived from Satellite VHRR with upper level low frequency current vectors. a. Thermal imagery for 12/16–22/90; current vectors for 1200 h 12/19. b. Thermal imagery for 3/3–9/91; current vectors for 1200 h 3/5. c. Thermal imagery for 3/10–16/91; current vectors for 1200 h 3/12. d. Thermal imagery for 3/17–23/91; current vectors for 1200 h 3/19.

December and January (Fig. 5a). Strong cyclonic shear and offshore increasing temperatures associated with the front were located near moorings A1 and B1, which resulted in strong eastward currents and increased temperatures at these sites (Figs. 3a, 4a). Currents at site A1 at this time were strongly sheared over depth and reached speeds greater than 100 $cm \cdot s^{-1}$ toward the east at the 75 m depth. This onshore position of the FC appears to coincide with the absence of a Loop Current and a sharp eastward turning of the Yucatan Current into the SSF, with little penetration into the Gulf of Mexico (Fig. 5a). Eastward current speeds began to decrease at A1 in the latter part of December, becoming 30 $cm \cdot s^{-1}$ or less toward the east for the period from 15 January to 18 February then reversing toward the west until about 10 April, when the flow abruptly shifted back toward the east and increased in speed to greater than 100 $cm \cdot s^{-1}$. The westward flow

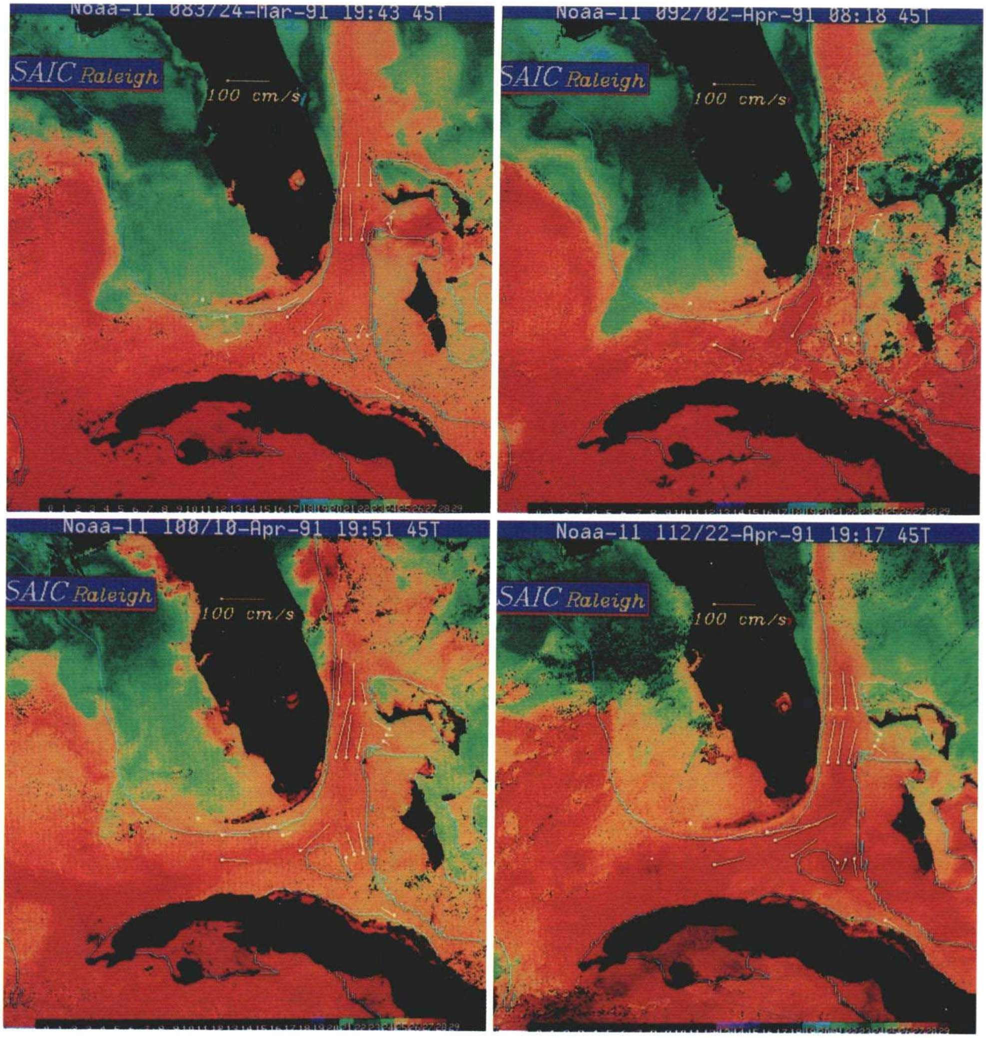

Figure 5. Surface thermal patterns derived from Satellite VHRR with upper level low frequency current vectors. e. Thermal imagery for 3/24–30/91; current vectors for 1200 h 3/26. f. Thermal imagery for 3/31–4/6/91; current vectors for 1200 h 4/2. g. Thermal imagery for 4/7–13/91; current vectors for 1200 h 4/9. h. Thermal imagery for 4/21–27/91; current vectors for 1200 h 4/23.

during March reached speeds of about 50 $cm{\cdot}s^{-1}$ and was accompanied by a 4°C drop in temperature, suggesting an offshore shift of the FC and the set-up of a cold, cyclonic circulation. The complete time sequence of satellite imagery (not shown) indicates that as the Loop Current penetrated northward into the Gulf of Mexico from 30 December to 18 February the FC near the Tortugas and transect A was shifting offshore. Apparently, when the Loop Current is well-developed, and flowing southward along the seaward edge of the southwest Florida shelf, it can overshoot the entrance to the SSF before turning eastward at about mid-channel between the Tortugas and Cuba (Fig. 5b, c). This Loop Current overshoot is also clearly evident in the pathlines of the 22°C isotherm at 100 m compiled by Maul (1977).

The offshore meander and recirculation feature appeared to move east of transect A about 10 April and was replaced by a following wave crest (onshore meander of the FC front). This resulted in an abrupt current reversal, with strong eastward flow and increasing temperatures at all sites on A (Figs. 3a, 4a). The increasing currents and temperatures occurred first at the offshore sites, resulting in a time lag that gives an average onshore movement of the FC front of about 5 km·d^{-1}. The downstream movement of the disturbance is also estimated at 5 km·d^{-1}, using the time lag of moored current and temperature variations between transects A and B, together with eastward displacements of the feature as determined from the satellite imagery.

The disturbance appeared to influence the flow and temperature fields at transect B from about 1–18 April (Figs. 3a, 4a, 5f, g). As the gyre moved past this section it caused an offshore shift of the FC axis, cyclonic current reversals and temperature drops that were in phase at stations B1, B2 and B3 on the cyclonic side of the current axis, and an increase in downstream current speeds coupled to a decrease in temperature on the anticyclonic side of the axis at station B4. A current reversal was also observed at the 30-m isobath on the B transect that was coherent and in phase with the reversal observed offshore. The termination of the gyre/meander at transect B was similar to that observed at transect A, consisting of an onshore shift of the FC as the trailing wave crest approached, which caused a reversal from westward to eastward flow and increasing temperature at sites shoreward of the axis. The speed of the onshore movement of the FC front as determined from the onshore phase lag of either increasing eastward currents or temperature was also similar to that found for transect A and for the downstream movement of the disturbance, or about 5 km·d^{-1}.

The movement of the gyre/meander through transect B and the offshore shift of the FC axis have a strong out of phase correlation with the current and temperature variability in Santaren Channel east of Cay Sal Bank (transect F: Figs. 3, 4 and spectra, not shown). When the FC shifted offshore at transect B in early April there followed, with about a 4-day lag, a sudden increase in northward flow and a decrease in temperature throughout the water column on the east side of transect F (Figs. 3a, 4a). Currents on the west side of the channel (F1) were out of phase with the flow on the east, but showed a similar temperature change, indicative of the set-up of a cyclonic eddy or current reversal within this channel. Satellite thermal imagery often show eddy-like current reversals across this channel (Fig. 5). The temperature minimum at 300 m during the April event was about 15°C across section F and appears to match the temperature at 300 m on the east side of section B. This indicates that as the FC shifted offshore there was a counterclockwise diversion of part of the flow around Cal Sal Bank and northward through the east side of transect F. It is not clear if part of the FC flow forced around Cal Sal Bank also entered the Old Bahama Channel, for there was only a single mooring (G1) placed in this channel and current and temperature variability there appear to be uncorrelated to fluctuations observed at other sites.

MAY–DECEMBER 91. Low-frequency current and temperature time series for May–December 91 are shown in Figures 3b and 4b. During this period the SEFCAR Project maintained coastal current meter moorings at the 30 m isobath at transects A, B and Dry Tortugas, and a near bottom ADCP at the 200 m isobath off the Tortugas (Fig. 2).

The full year of subtidal currents at the ADCP site off the Tortugas is shown in Figure 6 and indicates four periods of strong, persistent westward flow from May–August 91, September–November 91, December–January 92 and February–March 92. The duration of these westward flow events ranged from 40 to 108

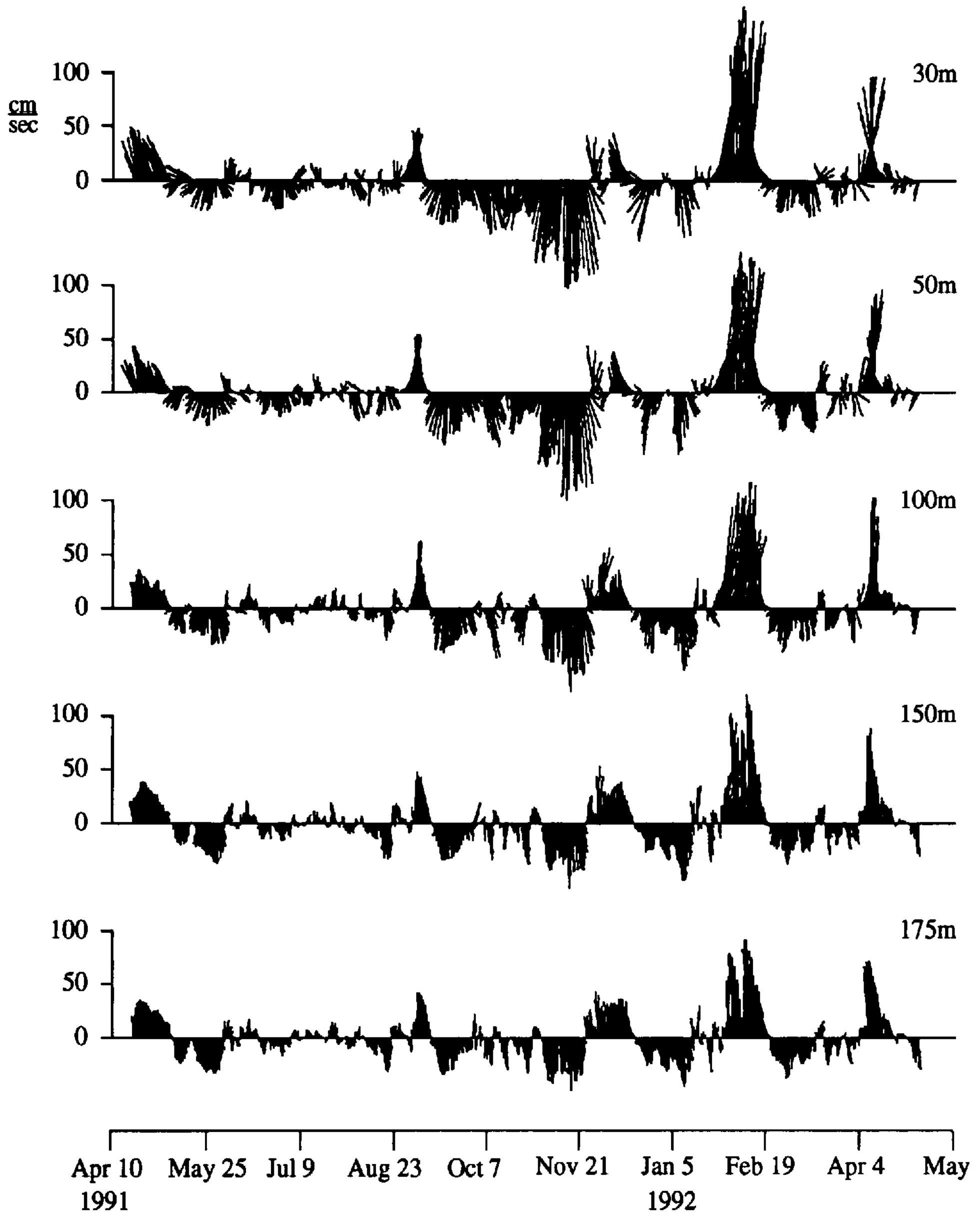

Figure 6. Vector time series of low-frequency currents from the ADCP on the 200-m isobath off the Dry Tortugas (DT). Vectors have been rotated 104°, water depths are given to the left.

days, and were interrupted by short bursts of intense eastward flow, lasting about 20 to 30 days. The duration of the summer event was 108 days and the fall event lasted 76 days. The fall event was particularly strong with westward speeds reaching 100 cm·s^{-1} at the ADCP. Intense eastward flow events occurred in the early part of May, September and December 91 and again in February 92. At the 30 m isobath off the Tortugas the flow was primarily toward the west throughout the measurement period (Fig. 3b).

The eastward propagation of westward flow events as observed in the current meter records at each transect indicates that the Tortugas recirculation features spread eastward and caused cold flow reversals off Marquesas on transect A from about 24 May to 5 September and again from 13 September to 29 October (Figs. 3b, 4b). These features moved downstream at approximately the same speed as observed in April (5 $km{\cdot}d^{-1}$). The cold recirculations caused westward flow on the shoreward side of B transect from about 28 August to 17 September and 27 October to about 6 November. Again the gyre at transect B was coupled to flow increases (decreases) on the eastern (western) side of Santaren Channel and a temperature drop throughout the channel, similar to the April event.

The durations of the Tortugas recirculations as observed at the Marquesas section were about 105 and 45 days for the summer and fall events, respectively. At the B transect off Looe Reef the durations of the summer and fall recirculations were 21 and 11 plus days, respectively. The shorter gyre duration at the eastward locations indicates that the gyre decreased in size as it approached the northward turn of the Straits of Florida, where the channel width decreases by about a factor of two, due to the presence of the Cay Sal Bank. Indeed, satellite thermal imagery show that for the April event, gyre dimensions decreased from about 90 × 150 km (cross-shore × alongshore distance) off the Tortugas to 70 × 120 km off Marquesas and approximately 60 × 100 km at transect B (Fig. 5e, f, g).

Hydrographic Surveys

The SEFCAR Project conducted several hydrographic surveys in the Tortugas/Marquesas region between May and July 91 that further documented the presence of a cold, cyclonic gyre centered about 40 km off the Dry Tortugas (Fig. 7a, b). The dimensions of the gyre were approximately 180 km in alongshore length and 100 km cross-shore, and remained relatively constant over the 1-month interval between surveys, although the eastern portion of the gyre extended further to the east and across the Marquesas section in the June survey. The cyclonic circulation of the gyre was supported by an upwelling of the thermocline of about 25 m in the center of the feature, near station 21C (Figs. 7, 8). The surface mixed layer ranged from a minimum of 5 m near the center of the gyre to about 30 m over the shelf (Fig. 8). The thermocline was located in the upper 150 m, consisting of a thermal strata between 13 and 29°C. The strongest part of the thermocline occurred in the central part of the gyre between the 23 to 27°C isotherms. Nutrient profiles show an uplifting of the nutricline to about 50 m from the surface near the gyre center at station 19C (Fig. 9b). Nitrate concentrations were about 10 μM at 100 m in the gyre center (Fig. 9b) and at the edge of the gyre influence the 10 μM level was at a depth of about 120 m (Fig. 9a). Without the gyre induced upwelling nitrate levels would be generally less than 0.1 μM at 50 m and from 1 to 3 μM at the 100 m level (Lee et al., 1992). Phosphate distributions also show a general uplifting associated with the gyre induced upwelling.

Chlorophyll values in early June were greater than 0.5 $\mu g{\cdot}liter^{-1}$ near the gyre center (Fig. 9c). This modest, but significant, enrichment is a probable response to the upwelled nutrients in the region. Abundances of copepod nauplii were also observed to be greatest near the gyre center in the early June survey (Fig. 9d). By late June chlorophyll and naupliar values had declined, but ammonia was high in the late June Tortuga section (Fig. 9b), suggesting areas of high grazing and secondary productivity.

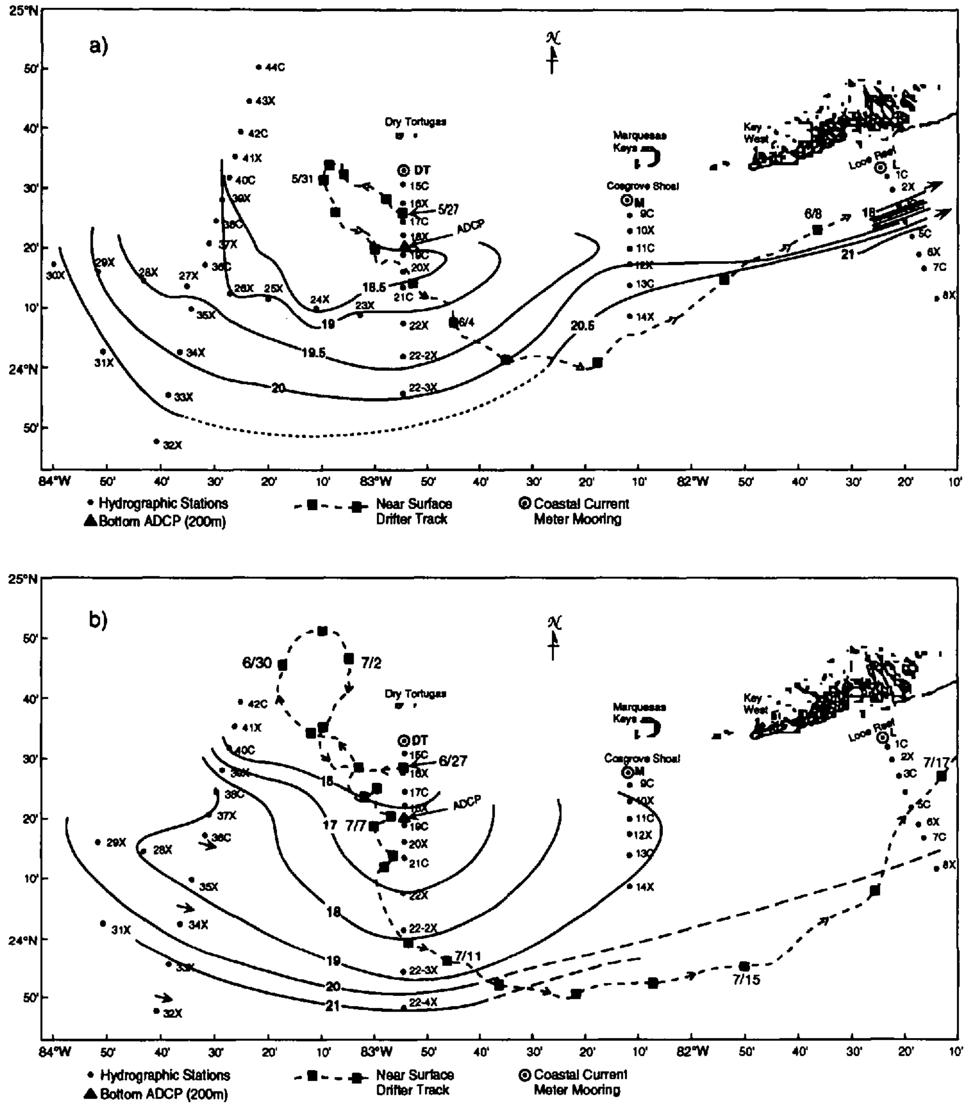

Figure 7. Temperature at 100 m. ARGOS satellite tracked, nearsurface drifter trajectory is superimposed. a. From the 24–27, May 1991 hydrographic survey. b. From the 25–27, June 1991 hydrographic survey.

Surface Drifter Trajectories

ARGOS satellite tracked nearsurface drifters were deployed on the northern side of the gyre during each hydrographic survey (Fig. 7a, b). Each drifter consisted of a PVC cylinder 0.1 m × 2.5 m, which served as the flotation and housed the transmitter, and a canvas drogue (sock with holes) 2 m × 5 m. The 10 m^2 area drogue was tethered to extend over depths of 3 to 8 m to track the flow in the surface mixed layer. The drifter design is a slight modification of the well-tested model developed by Bitterman and Hanson (1986). Trajectories of drifters deployed on 27 May and 27 June are remarkably similar and generally trace the

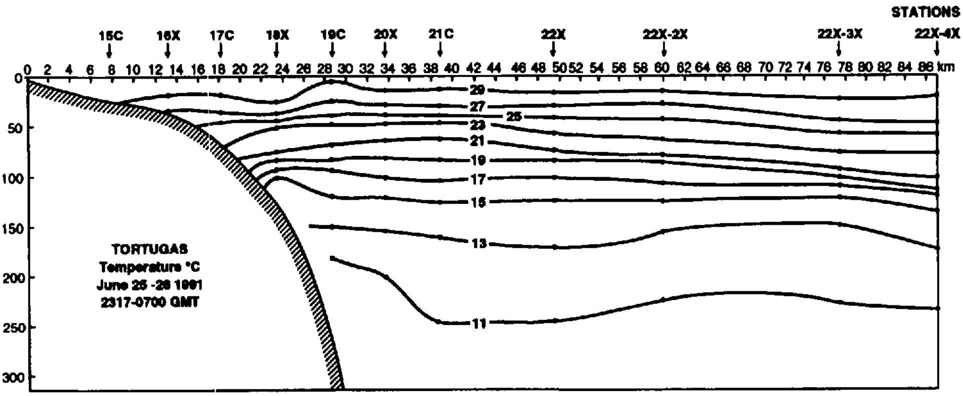

Figure 8. Dry Tortugas temperature section on 26 June 1991.

cyclonic circulation of the gyre as indicated by the 100 m temperature pattern (Fig. 7a, b). Interestingly, both drifters initially moved toward the WNW across a known mutton snapper spawning area, followed by offshore movement toward the SSE around the gyre, and then shoreward again in the vicinity of Looe Reef. Advective speeds generally ranged from 20 to 40 $cm \cdot s^{-1}$ within the gyre and increased to greater than 50 $cm \cdot s^{-1}$ after the drifters moved offshore and into the FC front.

A third drifter was deployed on 30 May on the northern side of the gyre, at the same location as the 27 May release (Fig. 10). This drifter spent the first 14 days in a tight recirculation in the gyre interior. On 12 June the drifter broke out of the gyre circulation and entered the channel between the Dry Tortugas and Rebecca Shoal where it stayed for about 10 days, undergoing tidal excursions of up to 7 km, but with no net through-flow. The drifter emerged north of the channel on 22 June and proceeded to follow the 20 m isobath east and northward along the southwest Florida shelf to a latitude of 25°50′N around the end of September. Next, the drifter moved on a general westward course, but with considerable north/south excursions that appear to be the result of cold front passages until about 5 January 1992, whereupon it merged with the Loop Current and was transported rapidly to the south at speeds that sometimes exceeded 100 $cm \cdot s^{-1}$. Entering the SSF the drifter appears to have been advected around a well developed cyclonic gyre off the Tortugas and approached within about 40 km of the coast of Cuba. Current measurements from the bottom mounted ADCP off the Tortugas during this period show a strong westward recirculation for December 1991 and January 1992 (Fig. 6: winter gyre). All together this drifter spent approximately 8 months in the southern Straits of Florida and southwest Florida shelf.

Discussion

The primary mode of subtidal current and temperature variability within the Straits of Florida appears to be associated with cross-channel shifts of the FC. This meandering mode produces an out of phase relationship in downstream currents on either side of the axis and in phase temperature change across the flow. Previous studies show that in the northern Straits the dominant period of the meandering mode falls within a 3 day to 3 week band and can be due to inherent barotropic or baroclinic instabilities of the flow and density fields (Boudra et al.,

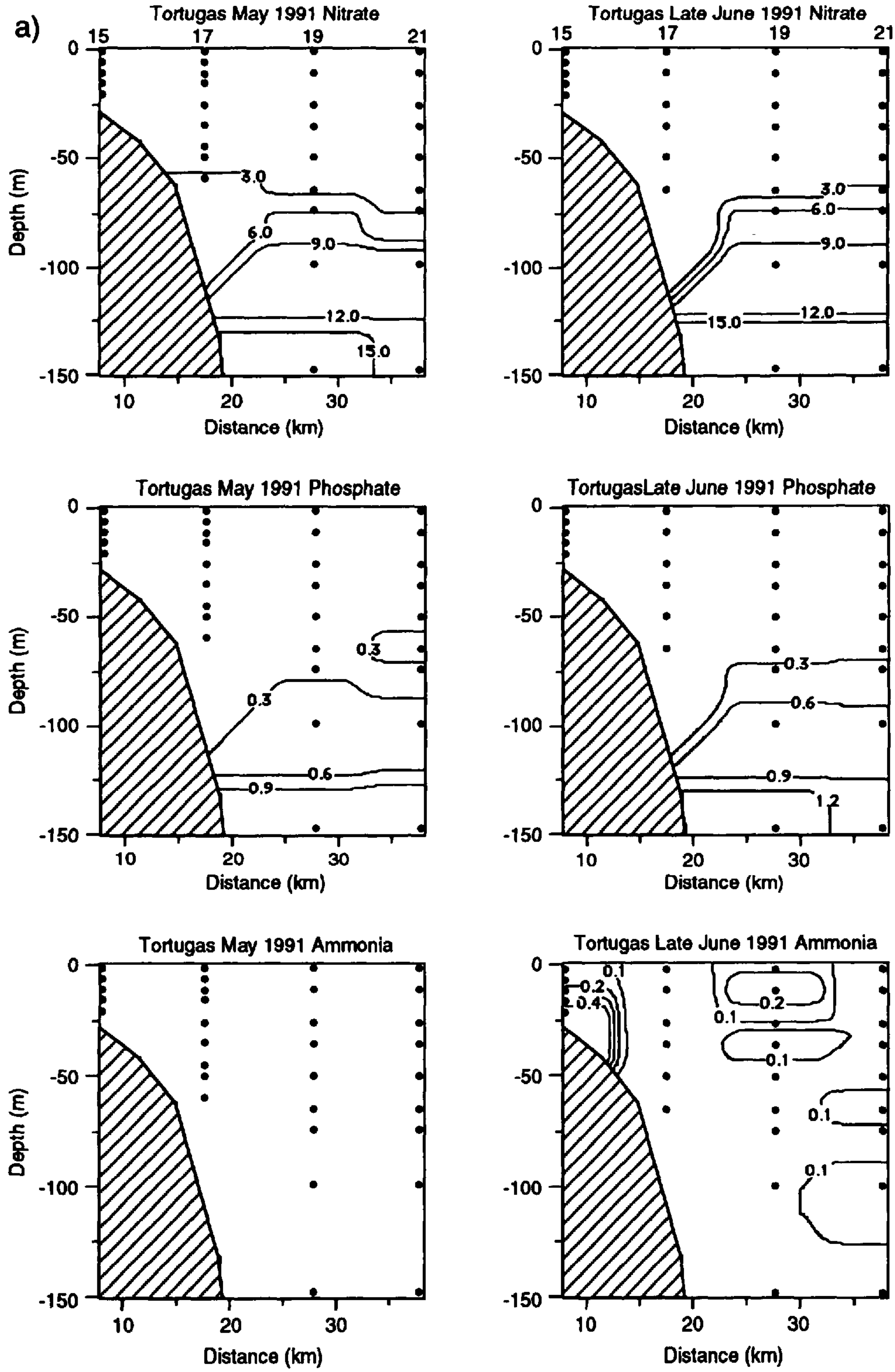

Figure 9a. Dry Tortugas nutrient (μM) sections in May and late June 1991.

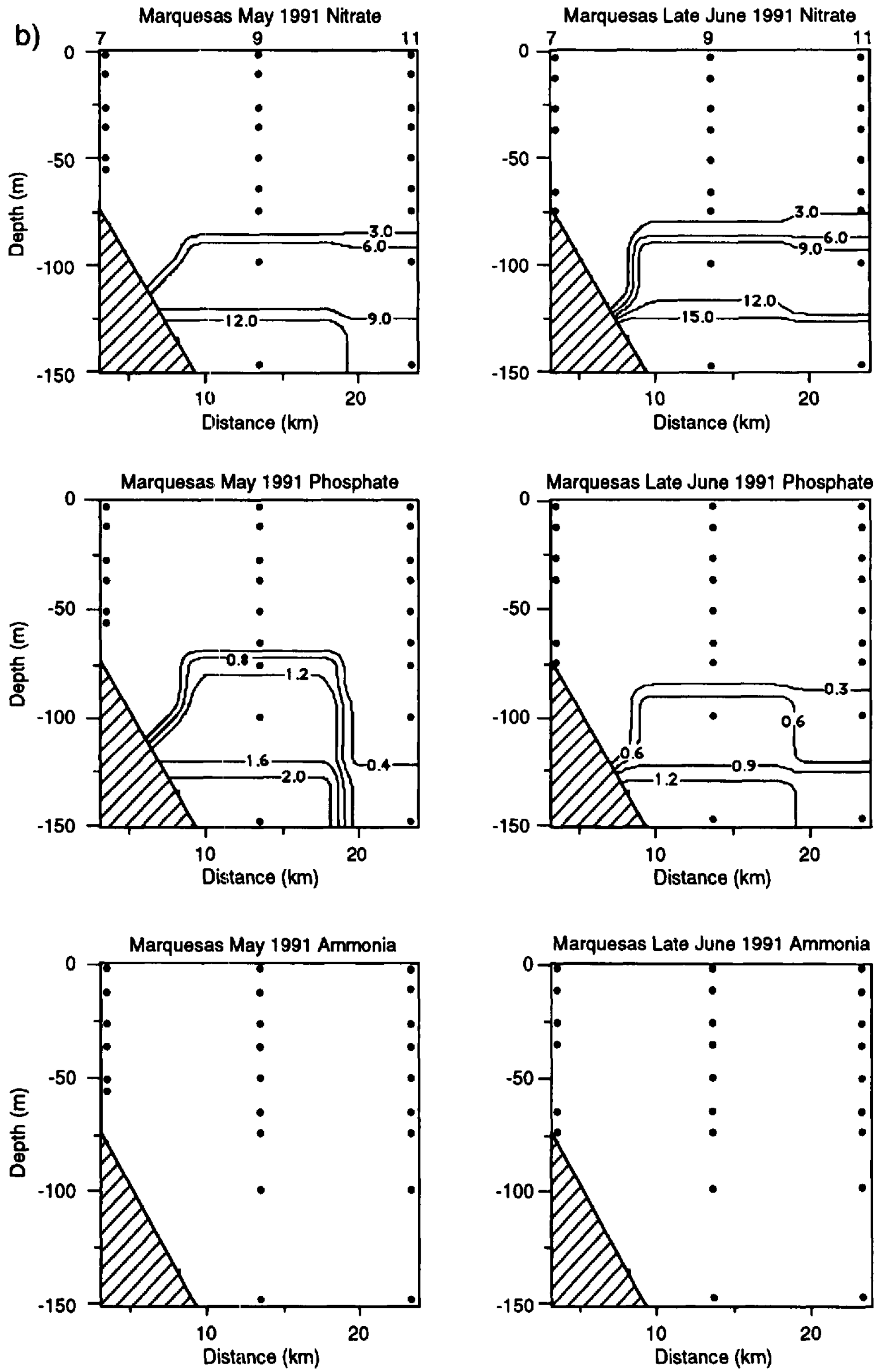

Figure 9b. Marquesas nutrient (μM) sections in May and late June 1991.

c)

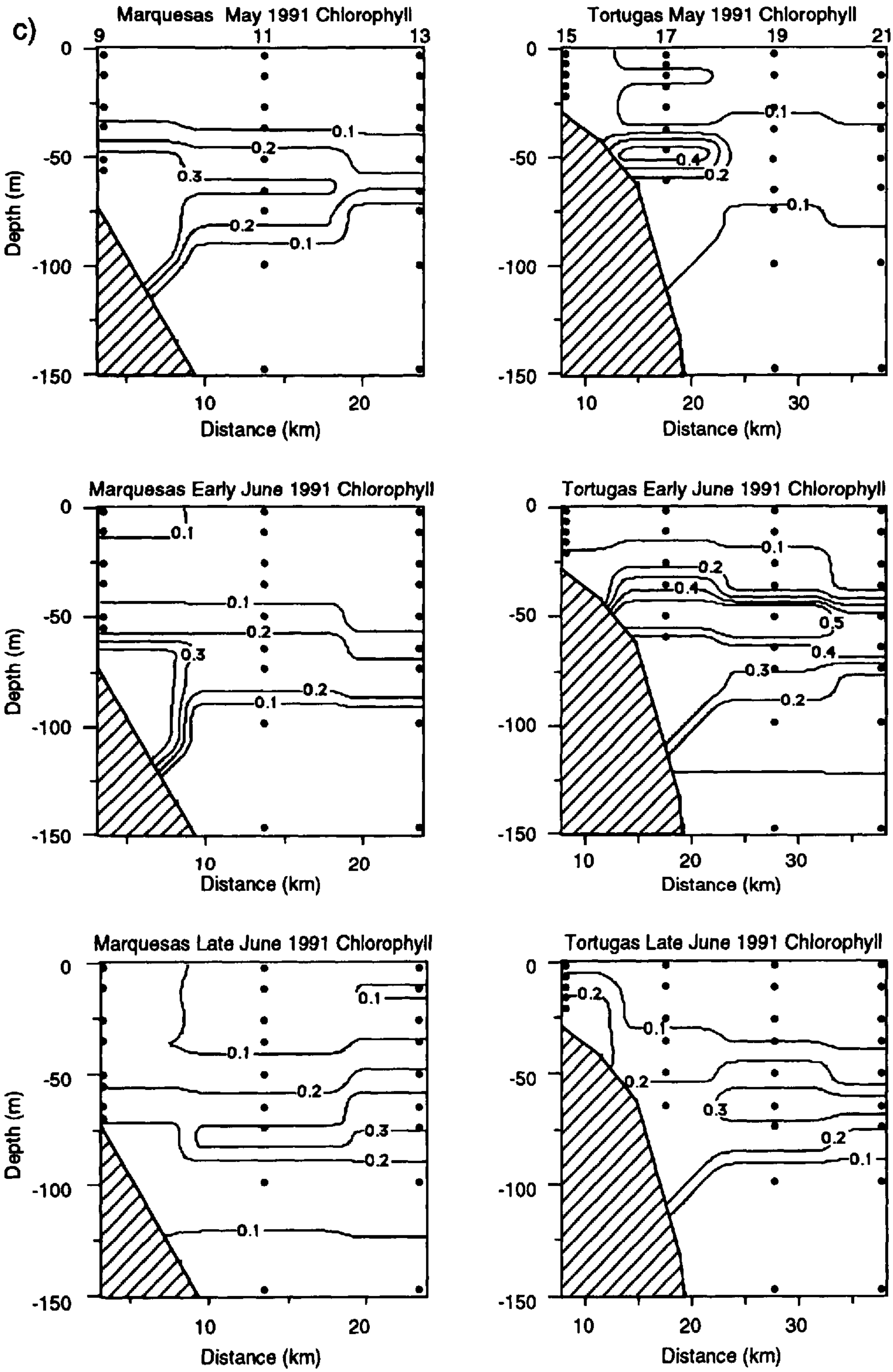

Figure 9c. Chlorophyll (μg·liter^{-1}) in sections at the Dry Tortugas and Marquesas in May 1991, early June 1991, and late June 1991.

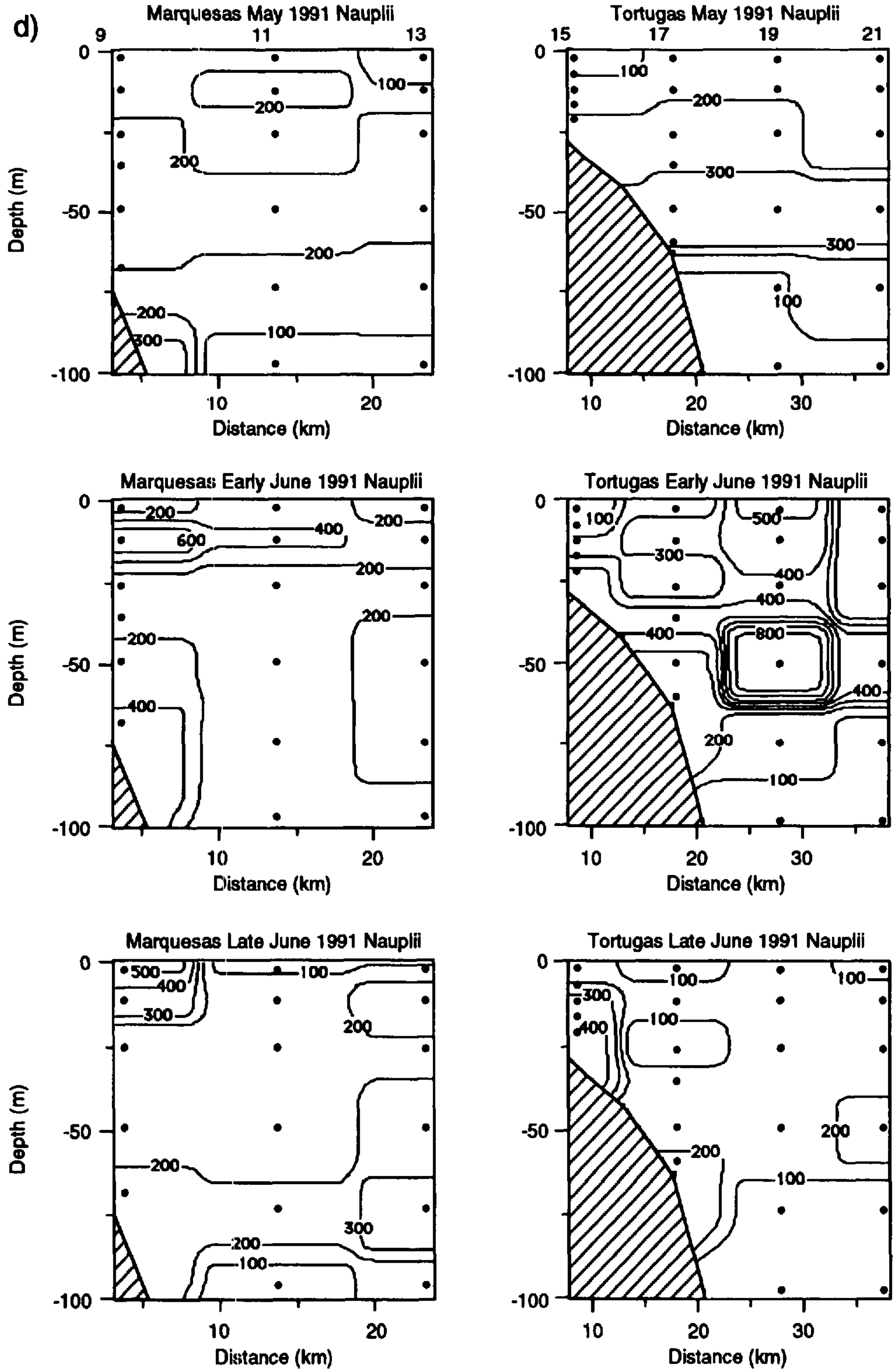

Figure 9d. Copepod nauplii (number·30 liter^{-1}) in sections at the Dry Tortugas and Marquesas in May 1991, early June 1991, and late June 1991.

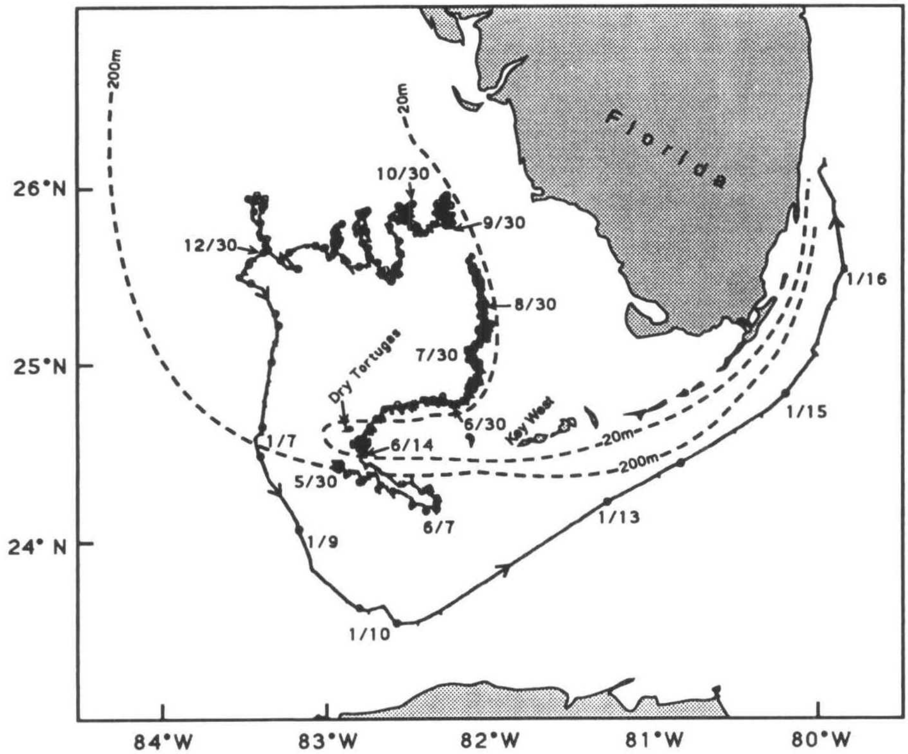

Figure 10. Nearsurface trajectory of ARGOS satellite tracked drifter for period 30 May 1991 to 17 January 1992.

1987, 1988), flow over topographic features such as the Miami Terrace (Lee and Mayer, 1977), and along-channel wind forcing (Brooks and Mooers, 1977a, 1977b). Cold, cyclonic frontal eddies are formed together with growing offshore meanders, as part of the baroclinic instability process (Lee, 1975; Lee and Mayer, 1977; Lee et al., 1991). These features have dimensions of tens of km and travel downstream at a mean speed of about 30 km·d^{-1} in the northern Straits. The passage of a frontal eddy can produce large current variations and even current reversals on the shoreward side of the FC, coupled to cold anomalies from upwelling in the core of the features.

In the SSF the offshore shift of the FC and the strong cyclonic curvature of the front at the western entrance provides a mechanism for the generation of a cyclonic gyre. The time sequence of satellite surface thermal imagery shows the spin-up and evolution of a gyre/offshore meander pair near the Tortugas in March of 1991 and its subsequent dramatic influence on the spatial and temporal variability of currents and temperature in the SSF (Figs. 3, 4, 5). The signature of the gyre in satellite derived surface temperature patterns consists of an offshore, cyclonic curvature of the FC front, with colder/upwelled waters in the gyre center and entrainment of a warm streamer from the leading wave crest (onshore meander of the FC front downstream of the gyre) that wraps around the northern or onshore portion of the gyre by the cyclonic flow field (Fig. 5c, e). This signature is similar to that found previously for FC frontal eddies and meanders in the northern Straits of Florida (Lee, 1975; Lee and Mayer, 1977) and in the South

Atlantic Bight (Lee and Atkinson, 1983) and along the Loop Current front (Paluszziewiez et al., 1983). However, FC frontal eddies are observed to move swiftly downstream at speeds of 30 to 35 km·d^{-1}, whereas, the gyres that formed off the Tortugas moved slowly toward the east at a mean speed of about 5 km·d^{-1}.

In the SSF the dominant period of FC meanders occurs in a 30 to 70 day band and the FC front can be displaced up to 100 km offshore during a meander. The cross-channel position of the axis appears to be strongly influenced by the manner in which the FC enters the southern straits from the eastern Gulf of Mexico, as well as by the disturbances that travel downstream along the cyclonic front. Satellite derived surface temperature patterns show that in December 1990 the Loop Current was nonexistent and the warm flow through the Yucatan channel turned abruptly to the east and entered the SSF with little penetration into the eastern Gulf of Mexico (Fig. 5a). This anticyclonic turning of the flow caused the northern boundary of the FC to extend close to the lower Florida Keys, resulting in strong downstream flows at the inshore moorings on transects A and B (Fig. 3). As the Loop Current grew northward into the eastern Gulf of Mexico the southward flow along the seaward edge of the southwest Florida shelf appears to overshoot the entrance to the SSF before turning abruptly to the east. The southward overshooting of the Loop Current, combined with the strong cyclonic curvature vorticity from the sharp eastward turning, appears to spin-up a cold cyclonic gyre offshore of the Dry Tortugas that we have named the Tortugas gyre (Fig. 5). Time series of satellite thermal imagery also indicate that further enhancement of this gyre may occur with encounters of Loop Current frontal eddies that sometimes propagate downstream into the region.

The duration of the gyre off the Tortugas is on the order of 100 days and its spatial scale is about 100 by 180 km. The demise of the gyre occurs with the approach of an onshore FC meander crest that sends the gyre toward the east at about 5 km·d^{-1} and causes a rapid decrease in size. By the time the March/April 1991 gyre event reached transect B in the region of the Pourtales Terrace it had decreased in size to about 60 by 100 km (Fig. 5g). Presumably the decrease in size is due to the narrowing of the channel caused by the presence of the Cal Sal Bank. Oey (1988) showed that the growth of finite amplitude disturbances in the Gulf Stream front off the southeast U.S. is dependent on the cross-stream distance from the slope to the Gulf Stream axis. This distance decreases as the gyre approaches transect B, which may account for the gyre decay. Previous SEFCAR studies of gyre formation off the middle and lower keys suggested a preference for gyre formation on the Pourtales Terrace and therefore referred to this feature as the Pourtales gyre (Lee et al., 1992). With the aid of time series of satellite thermal imagery and the large-scale moored array that covered the entire Florida Straits, we now have clearly established that the previously studied Pourtales gyre is a latter stage in the evolution of the Tortugas gyre.

Implications for the Recruitment of Fish and Lobster Larvae

Our previous study (Lee et al., 1992) showed that the cyclonic circulation of the Pourtales gyre combined with onshore surface Ekman transports from prevailing westward winds could have a strong influence on the transport and recruitment of fish and lobster larvae into the coral reefs of the Florida Keys. Upwelling in the gyre interior of about 2 m·d^{-1} uplifts the nutricline into the euphotic zone causing enhanced production. The observed new nutrient supply was coincident with increased concentrations of copepod nauplii, which is a possible food supply for fish and lobster larvae. The nauplii are concentrated within the gyre and coastal boundary zone by the controlling physics i.e., flow convergence zones in the presence of the coastal boundary and thermal strata, as shown schematically in Figure 11. Lee et al. (1992) found that the gyre circulation could be influential in retaining locally spawned fish and slipper lobster (genus *Scyllarus*) larvae for recruitment into the Florida Keys reefs, since both the duration of the gyre in the vicinity of the Pourtales Terrace and the planktonic stage for grouper and snapper larvae (Leis, 1987) and slipper lobster larvae (Robertson, 1968) were on the order of 1 month. However, it was felt that the gyre duration was too short to be a factor in the recruitment of locally spawned spiny lobster larvae, *Panulirus,* which has a 6 to 12 month planktonic stage (Lewis, 1951; Sims and Ingle, 1966). Thus, lobster recruits would be derived from either an upstream source for *Panulirus* larvae, or larvae retention on the southwest Florida shelf for periods on the order of 6 months. Our recent drifter releases provide evidence that retention of *Panulirus* larvae on the southwest Florida shelf for periods of up to 8 months can occur (Fig. 10). The drifter tracks indicate that there is a significant potential for local recruitment of *Panulirus* larvae spawned in the Dry Tortugas region. Schematic representations of possible recruitment pathways in the lower and western keys are shown in Figure 12. The pathway through the southwest Florida shelf, which combines the circulation influences of the Tortugas gyre, southwest Florida shelf wind driven circulation and the Loop Current, is the only route with sufficient duration to be a factor in retaining local spiny lobster recruits. By contrast, locally spawned snapper and grouper larvae can be retained for the duration of their planktonic stages by either the Pourtales gyre or the Tortugas gyre. If gyres are not present during *Panulirus* spawning, larvae will most likely be advected out of the Straits of Florida by the FC. Snapper/grouper larvae, on the other hand, could still be retained in the coastal waters if onshore Ekman transports from the prevailing westward winds are sufficient to remove them from the FC.

Current records from the waters offshore of the Dry Tortugas indicate that the duration of the Tortugas gyre ranges from 40 to 108 days in this region (Fig. 6). The intervals between gyre recirculation periods are characterized by short bursts of intense eastward flow lasting 20 to 30 days. During the full year of current meter observations, the Tortugas recirculation appears to have influenced water motions in the western keys for approximately 70% of the time, and almost 90% of the time during the 7-month period from May through November 1991. Spawning of mutton snapper is known to occur at a location about 20 km southwest of the Tortugas during the full moon cycles of May and June. The occurrence of gyre recirculation during this time and the trajectories of nearsurface drifters (Figs. 7a, b, 10) indicate that larval transport was controlled by the combined influences of the gyre circulation and wind induced Ekman transports. Recruitment of these larvae could have been spread between the Tortugas and the middle keys, but with the greatest concentration of recruits located in the Tortugas.

In addition to having an effect on the offshore planktonic trophic resources, upwelling associated with gyre formation may have had a long-term effect on the ecology and geomorphology of the southeast Florida region. Bank-barrier reefs located >10 km offshore of the Florida Keys are an outstanding feature of the area. One to 2 km offshore of the presently emergent reefs, there are several lines of submerged "outlier" reefs at ~15 to 20 m depth, with Holocene and pre-Holocene accumulations on a Pleistocene platform (Lidz et al., 1991). These reefs are "give-up reefs" (Neumann and Macintyre, 1985) that ceased growing at various times since the Pleistocene. Periods of increased upwelling may have been

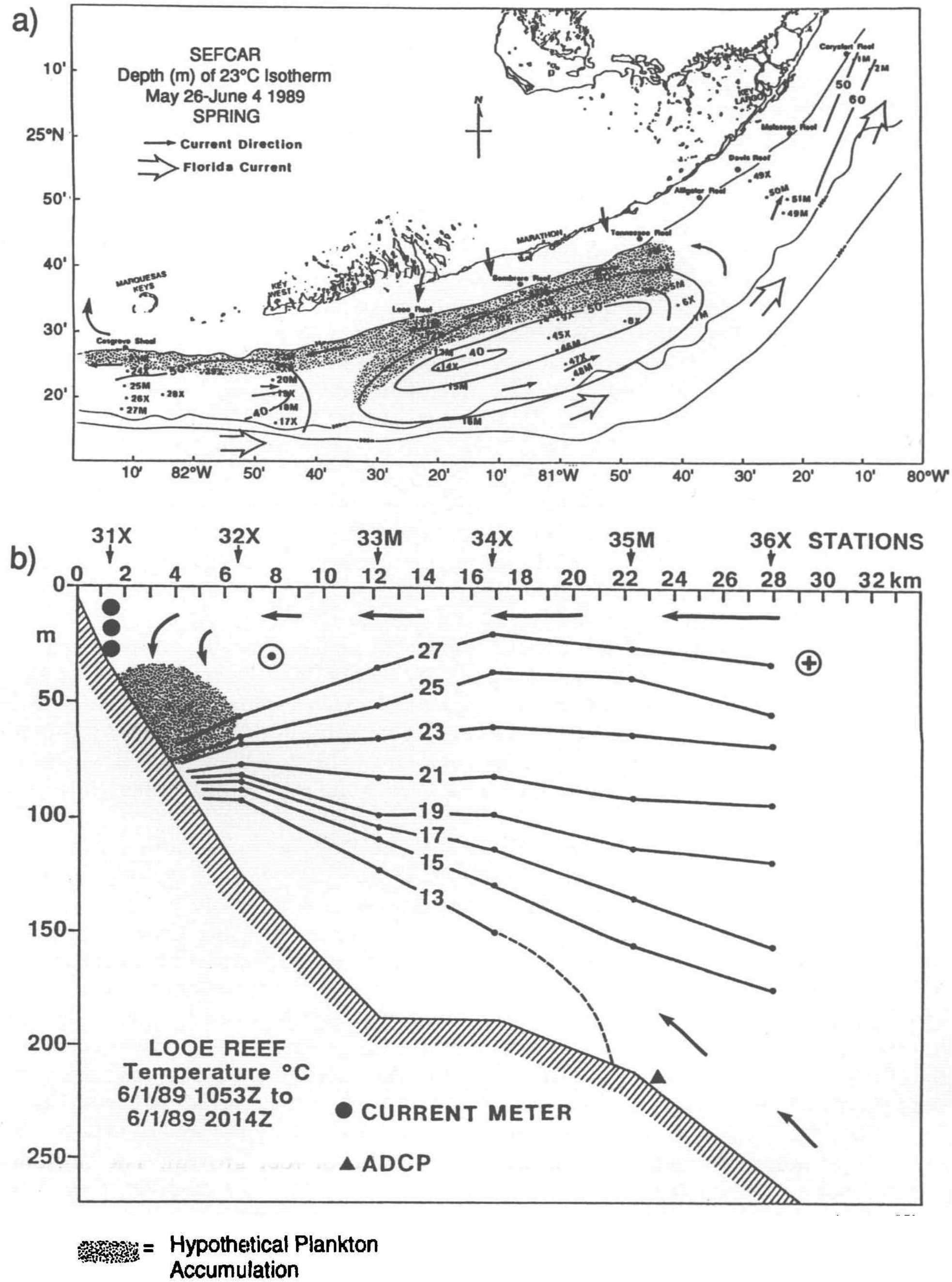

Figure 11. (a) and (b). Schematic of larvae concentrations due to influence of Pourtales gyre circulation and prevailing easterly winds (towards west), superimposed on the spring survey temperature distribution (figure 12, from Lee et al., 1992).

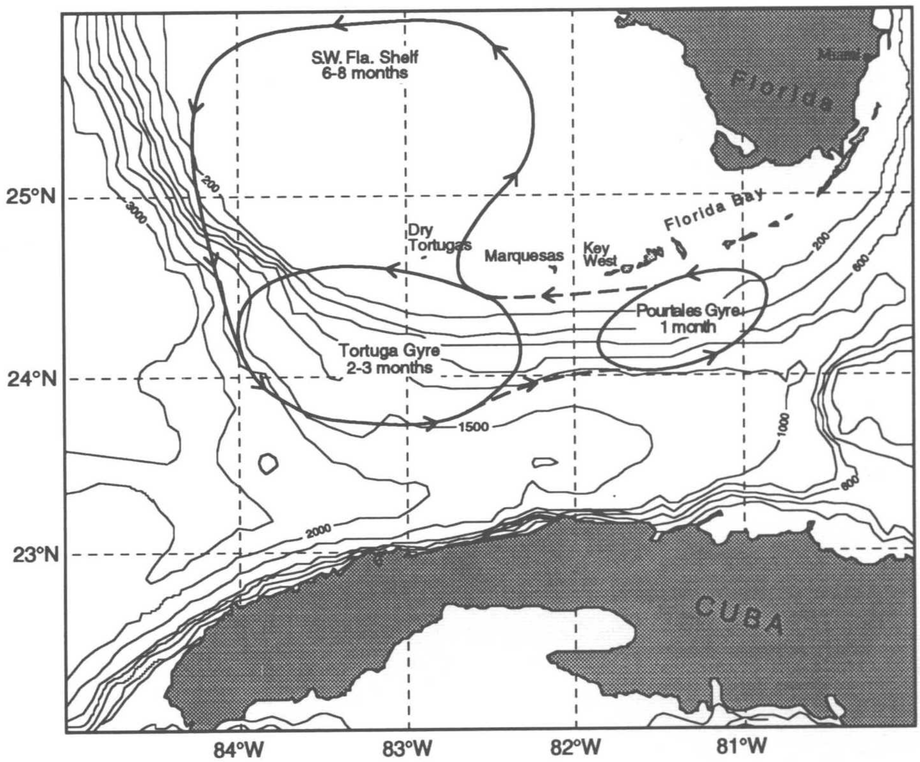

Figure 12. Schematic of possible recruitment pathways for locally spawned fish and lobster larvae in the lower and western Florida Keys.

responsible for stifling the growth of these reefs (Hines, 1993). Upwelling has been attributed with both increased coral reef productivity (Smith, 1983) and with preventing or slowing reef formation (Hallock and Schlager, 1986) due to domination of the reef-building corals by macroalgae (Littler and Littler, 1985). The effect of upwelling on reefs may well be related to the distance from the reef at which upwelling takes place. At the present time, most of the nutrients upwelled by the Tortugas Gyre are assimilated into the food chain a distance offshore from the reefs, and few incidences of upwelling-derived elevated nutrients have been observed on the reefs (Lapointe, 1986). However during lower stands of sea level such as those 10,000 YBP, gyre waters may have bathed the outlier reefs more directly or frequently, and upwelled nutrients may have caused a community shift away from hermatypic corals resulting in cessation of reef growth. The present day impact of upwelled nutrients on Florida Reef Track coral reefs is unknown but should be taken into consideration in studies of potential anthropogenic nutrient impacts.

SUMMARY

Low-frequency current and temperature variability in the Straits of Florida results primarily from a mix of onshore/offshore meandering of the FC axis, formation and evolution of gyres and eddies, and response to local and remote wind forcing. In the southern Straits of Florida, below 25°N latitude, the dominant mode of variability consists of a large-scale meander of the FC coupled to the formation of a cold, cyclonic gyre off the Dry Tortugas. The offshore position of the FC in this region appears to be strongly dependent upon the development of the Loop Current in the eastern Gulf of Mexico and the occurrence of frontal eddies that propagate along the Loop Current eastern boundary. The absence of a Loop Current coincides with strong eastward flow in the coastal boundary zone off the western keys of the Dry Tortugas and Marquesas. With a well developed Loop Current, southward flow along the shelf edge of the SW Florida shelf will overshoot the entrance to the southern Straits of Florida before abruptly turning to the east off the Tortugas. This offshore displacement of the flow, coupled to strong cyclonic curvature vorticity appears to spin-up a cold, cyclonic gyre off the Tortugas that we have named the Tortugas gyre. The gyre can be further enhanced or temporarily displaced by the occurrence of smaller scale frontal eddies and meanders. Onshore/offshore shifts of the FC front in this region can be up to 100 km with a mean period of 60 days. Duration of the Tortugas gyre is on the order of 100 days and spatial scales can be approximately 180 km alongshore and 100 km cross-shore. The demise of the gyre can occur with the approach of an onshore meander crest from a propagating frontal disturbance or the pinch-off of a Loop Current ring that enables the Yucatan Current to short-circuit the eastern Gulf and turn directly into the southern Straits of Florida. The time scale for ring formation ranges from approximately 8.5 to 12 months (Maul, 1977; Sturges, 1992; Maul and Vukovich, 1993). With the approach of a meander crest the Tortugas gyre is forced to the east at a mean speed of about 5 $km \cdot d^{-1}$ and decreases in size, presumably due to the narrowing of the channel due to the presence of the Cal Sal Bank. When the gyre reaches the Pourtales Terrace region offshore of Big Pine Key and Marathon, it is reduced to about half its original size off the Tortugas. Gyre features have not been observed off the northern keys, where the distance from the slope to the FC axis is greatly decreased. With the aid of time series of satellite thermal imagery and observations from the large-scale moored array that covered the entire Straits of Florida we now have clearly established that the previously studied Pourtales gyre (Lee et al., 1992) is a latter stage in the evolution of the Tortugas gyre.

The evolution of recirculating gyres in the western and lower Florida Keys has a profound influence on the transport, survival and recruitment of fish and lobster larvae. Upwelling in the gyre interior provides elevated nutrient levels to fuel increased primary productivity and micro zooplankton concentrations. The enhanced potential larval food supply may result in increased larval fish survival. Previous observations of larval fish abundance in the Florida Keys coastal waters show concentrations spread over the upper 150 m, with maximum abundances in the upper 50 m coincident with our observed peak concentrations of nauplii (Cha et al., 1994). Gyre durations are on the order of 100 days, which are sufficient to retain snapper and grouper larvae over their planktonic stages. Gyre cyclonic circulation, together with prevailing westward winds provide a transport mechanism for onshore advection of larval fishes to the coral reefs between the Tortugas and the middle keys. Horizontal flow convergences and thermal strata can concentrate larvae and available food supply in frontal regions to further enhance survivability. However, flow convergences can also increase the number of predators.

An 8-month trajectory of a satellite tracked nearsurface drifter shows that a recruitment pathway can exist for spiny lobster larvae spawned locally off the Tortugas with retention in the southwest Florida shelf and return to the Tortugas via the Loop Current and the Tortugas recirculation.

The lower keys region appears to be a preferred area for onshore surface transport due to the prevailing westward winds and coastal gyre circulations. North of the lower keys coastal gyres do not occur in the Straits of Florida due to the narrowing of the channel. Furthermore, the prevailing southeast winds no longer cause onshore Ekman transports due to the change in orientation of the Straits of Florida from east/west to north/south. Thus, the combination of the FC eastward jet, coastal gyres and prevailing westward winds in the lower keys can enhance onshore Ekman transports resulting in a region of preferential shoreward movement of passive materials in the surface layer, such as plankton, or contaminants, in the event of an accidental discharge offshore or upstream, of contaminants such as oil slicks.

Acknowledgments

Many thanks to SEFCAR colleagues M. McGowan and C. Rooth for helpful discussions on the Tortugas gyre and cruise participation to find this feature. We also thank the crew of the University of Texas Research Vessel Longhorn for their assistance and good humor during the survey cruises and the RSMAS Ocean Technology Group for preparing the coastal moored instrumentation. Support for this work was provided by Minerals Management Service, Atlantic OCS Regional Office, Contract No. 14-35-0001-30493, and NOAA/CIMAS through contract NA85-WC-H-06134. Research within the Florida Keys National Marine Sanctuary was conducted under National Marine Sanctuary Research Permit KLNMS and LKNMS-11-89.

Literature Cited

Bitterman, D. S. and Donald V. Hanson. 1986. The design of a low cost tropical drifter buoy. Proceedings MDS '86: Marine Data Systems International Symposium.

Boudra, D., R. Bleck and F. Schott. 1987. Study of transport fluctuations and meandering of the Florida Current using an isopycnic coordinate numerical model. Pages 149–168 *in* J. C. J. Nihoul and B. M. Jimart, eds. Three dimensional models of marine and estuarine dynamics. Elsevier Oceanography series, vol. 45. Elsevier.

———, ——— and ———. 1988. A numerical model of instabilities in the Florida Current. J. Mar. Res. 46: 715–751.

Brooks, D. A. and C. N. K. Mooers. 1977a. Wind forced continental shelf waves in the Florida Current. J. Geophys. Res. 82: 2569–2576.

——— and ———. 1977b. Free, stable continental shelf waves in a sheared, barotropic boundary current. J. Phys. Oceanogr. 7: 380–388.

Brooks, I. 1979. Fluctuations in the transport of the Florida Current at periods between tidal and two weeks. J. Phys. Oceanogr. 9: 1048–1053.

——— and P. P. Niiler. 1975. The Florida Current at Key West: Summer 1972. J. Mar. Res. 33: 83–92.

Cha, S. S., M. F. McGowan and W. J. Richards. 1994. Vertical distribution of fish larvae off the Florida Keys, 26 May–5 June 1989. Bull. Mar. Sci. 54: 828–842.

Chew, F. 1974. The turning process in meandering currents: a case study. J. Phys. Oceanogr. 4: 27–57.

Duing, W. 1975. Synoptic studies of transients in the Florida Current. J. Mar. Res. 33: 53–73.

———, C. N. K. Mooers and T. N. Lee. 1977. Low-frequency variability in the Florida Current and relations to atmospheric forcing from 1972 to 1974. J. Mar. Res. 35: 129–161.

Hallock, P. and W. Schlager. 1986. Nutrient excess and the demise of coral reefs and carbonate platforms. Palaios 1: 389–398.

Hines, Albert C. 1993. Structural, stratigraphic, paleoceanographic development of the margins of the Florida Platform. Page 93 *in* A. F. Randazzo and D. S. Jones, eds. Geology of Florida. Chapter 11.

Johns, W. E. and F. Schott. 1987. Meandering and transport variations of the Florida Current. J. Phys. Oceanogr. 17: 1128–1147.

Lapointe, B. E. 1986. Upwelling as a source of "new" nutrients to Looe Key National Marine Sanctuary. EOS 67: 992 (Abstract).

Leaman, K., R. Molinari and P. Vertes. 1987. Structure and variability of the Florida Current at 27°N: April 1982–July 1984. J. Phys. Oceanogr. 17: 565–583.

Lee, T. N. 1975. Florida Current spin-off eddies. Deep-sea Res. 22: 753–763.

——— and L. P. Atkinson. 1983. Low-frequency current and temperature variability from Gulf

Stream frontal eddies and atmospheric forcing along the southeast U.S. outer continental shelf. J. Geophys. Res. 88: 4541–4568.

——— and D. A. Mayer. 1977. Low-frequency current variability and spin-off Southeast Florida. J. Mar. Res. 35: 193–220.

———, F. Schott and R. Zantopp. 1985. Florida Current: low frequency variability of the Florida Current as observed with moored current meter stations during April 1982–June 1983. Science 227: 298–301.

———, J. A. Yoder and L. P. Atkinson. 1991. Gulf Stream frontal eddy influence on productivity of the southeast U.S. continental shelf. J. Geophys. Res. 96: 22191–22205.

———, C. Rooth, E. Williams, M. McGowan, A. F. Szmant and M. E. Clarke. 1992. Influence of Florida Current, gyres and wind-driven circulation on transport of larvae and recruitment in the Florida Keys coral reefs. Cont. Shelf Res. 12: 971–1002.

Leis, J. M. 1987. Review of early life history of tropical groupers (Serranidae) and snappers (Lutjanidae). Pages 189–237 *in* J. J. Polovina and S. Ralston, eds. Tropical snapper and groupers: biology and fisheries management. West View Press, Boulder.

Lewis, J. B. 1951. The phyllosoma larvae of the spiny lobster *Panulirus argus*. Bull. Mar. Sci. Gulf Carib. 1: 89–103.

Lidz, Barbara H., Albert C. Hine, Eugene A. Shinn and Jack L. Kindinger. 1991. Multiple outer-reef tracks along the south Florida bank margin: outlier reefs, a new windward-margin model. Geology 19: 115–118.

Littler, M. M. and D. S. Littler. 1985. Factors controlling relative dominance of primary producers on biotic reefs. Proc. 5th Internat. Coral Reef Congr., Vol 4: 35–39.

Maul, G. 1977. The annual cycle of the Gulf Loop Current Part I: observations during a one-year time series. J. Mar. Res. 35: 29–47.

——— and F. Vukovich. 1993. The relationship between variations in the Gulf of Mexico Loop Current and Straits of Florida volume transport. J. Phys. Oceanogr. 23: 785–796.

Molinari, R. 1980. Current variability and its relation to sea-surface topography in the Caribbean Sea and Gulf of Mexico. Mar. Geod. 3: 409–436.

Neumann, A. C. and I. G. Macintyre. 1985. Reef response to sea-level rise: keep-up, catch-up, or give-up. Pages 105–110 *in* Proceedings of the Fifth International Coral Reef Symposium 3.

Oey, L. 1988. A model of Gulf Stream frontal instabilities, meanders and eddies along the continental slope. J. Phys. Oceanogr. 18: 211–229.

Paluszkiewicz, T., L. P. Atkinson, E. S. Posmentier and C. R. McClain. 1983. Observations of a Loop Current frontal eddy intrusion onto the west Florida shelf. J. Geophys. Res. 88: 9639–9652.

Robertson, P. B. 1968. The complete larval development of the sand lobster *Scyllarus Americanus* (Smith) (*Decopoda, Scyllaridae*) in the laboratory, with notes on larvae from the plankton. Bull. Mar. Sci. 18: 294–342.

Schott, F., T. N. Lee and R. Zantopp. 1988. Variability of structure and transport of the Florida Current in the period range of days to seasonal. J. Phys. Oceanogr. 18: 1209–1230.

SAIC. 1992. Straits of Florida Physical Oceanographic Field Study. Final Interpretive Report Vol. II. Prepared for Minerals Management Service by Science Applications International Corp., Raleigh, N.C., OCS Study #920024, 174 pp.

Schmitz, W. and P. L. Richardson. 1991. On the sources of the Florida Current. Deep-Sea Res., 38(Suppl. 1): 5379–5409.

Sims, H. W., Jr. and R. M. Ingle. 1966. Caribbean recruitment of Florida's spring lobster population. Quart. J. Fla. Acad. Sci. 29: 207–243.

Smith, S. V. 1983. Net production of coral reef ecosystems. Pages 127–131 *in* M. Reaka, ed. The ecology of deep and shallow reefs. NOAA Undersea Res. Prog. Ser. Vol. 1.

Sturges, W. 1992. An estimate of the spectrum of Loop Current variability from gappy data. J. Phys. Oceanogr. 22: 1245–1256.

Vukovich, F. M. 1988. On the formation of elongated cold perturbations off the Dry Tortugas. J. Phys. Oceanogr. 18: 1051–1059.

DATE ACCEPTED: January 27, 1994.

ADDRESSES: *(TNL) (MEC) (EW) (AFS) University of Miami Rosenstiel School of Marine and Atmospheric Science, 4600 Rickenbacker Causeway, Miami, Florida 33149. (TB) Science Applications International Corporation, 615 Oberlin Road, Suite 300, Raleigh, North Carolina 27605.*