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Influence of Florida Current, gyres and wind-driven circulation on transport of larvae and recruitment in the Florida Keys coral reefs

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Abstract—Physical processes with high potential influence on the transport and recruitment of fish, lobster and other larvae in the Florida Keys are discussed using current measurements from standard moored instrumentation, plus bottom mounted Acoustic Doppler Current Profile observations, interdisciplinary surveys of water mass properties, nutrients and planktonic distributions, and satellite derived surface thermal patterns. A cold, cyclonic gyre forms over the Pourtales Terrace seaward of the middle and lower Keys where the Florida Current shifts from eastward to northward flow. Formation of the gyre appears to be related to offshore meander motion of the Florida Current and its cyclonic curvature. Prevailing easterly winds over the gyre circulation cause a convergence of Ekman transports into the coastal zone. The gyre circulation combined with the shoreward convergence of Ekman flow facilitates the transport of pelagic larvae from the Current to the fringing reefs. Duration of the gyre is approximately 1 month, which matches the planktonic stage of fish and slipper lobster larvae, and thus provides a mechanism for larvae retention and local recruitment. Abundant microzooplankton food supply for the larvae is available in the gyre interior due in part to concentration mechanisms and ecosystem response to gyre-induced upwelling of deeper, nutrient enriched waters. Gyre retention times are too short to be a factor in recruitment of locally spawned Florida spiny lobster larvae, which have a planktonic stage that may last up to 12 months. This indicates that Florida spiny lobster should recruit from remote upstream sources in the Caribbean or spend most of their long planktonic stage in Florida Bay of the southwest Florida shelf.

1. INTRODUCTION

THE physical processes controlling the recruitment of lobster and fish larvae in the Florida Keys are poorly understood at present. It is not known if larval recruitment is due to retention in local waters or transport from remote upstream sources. Successful management of the fishery is dependent on improved understanding of the recruitment process. Little is known about the flow variability in the southern Straits of Florida. The South and East Florida Caribbean Recruitment study (SEFCAR) was designed as an interdisciplinary investigation of physical transport mechanisms, together with larvae and microzooplankton distributions to better understand recruitment processes in the Florida Keys. In this manuscript we present findings from the first year of physical measurements showing

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the existence of local recirculation features and coastal wind driven flows that have important implications for fish and lobster larvae concentrations and their successful recruitment to Florida Keys reefs.

2. BACKGROUND

Confined within the Straits of Florida is the strong northward flowing Florida Current (FC), the portion of the Gulf Stream system which connects the Loop Current in the eastern Gulf of Mexico to the Gulf Stream off the southeast U.S., SCHMITZ and RICHARDSON (1991) estimate that roughly 45% of the water flowing through the Straits of Florida originates in the South Atlantic. They report that upper layer FC waters, with temperature greater than 24°C, are derived primarily from the tropical South Atlantic. Waters in the temperature range of 12–24°C consist mostly of Subtropical Underwater (SUW) of North Atlantic origin, which has a distinct salinity maximum. Waters in the temperature range of 7–12°C are associated with a distinct salinity minimum, the dominant source of which is Antarctic Intermediate Water acquired from the South Atlantic. These water masses combine in the Caribbean due to the convergence of the North Brazil Current and the wind driven subtropical gyre to form the intense Loop Current/Florida Current that directly influences the coastal flows in our study area (Fig. 1).

The axis of the FC is located about 25 km offshore of Miami, Florida, and Palm Beach, Florida, in the northern Straits of Florida on the mean (MOLINARI and LEAMAN, 1987) and 80 km offshore of Key West, Florida, in the southern Straits where a mean westward

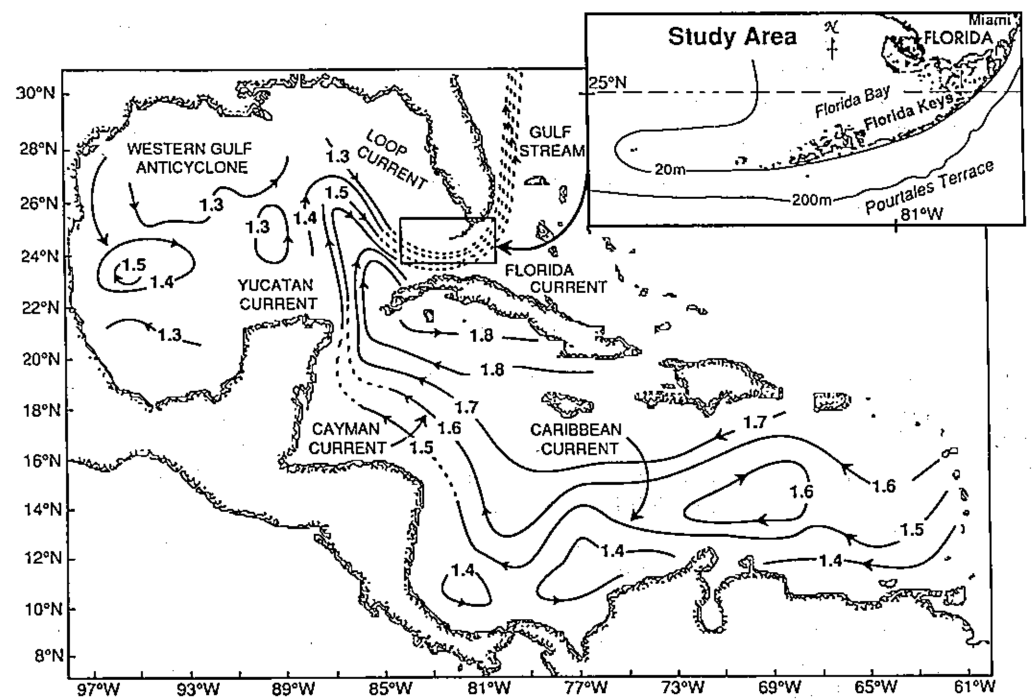

Fig. 1. Location of study area and major current systems as determined from mean annual dynamical topography (dyn m) adapted from MOLINARI (1980; Fig. 2).

countercurrent has been observed on the shoreward side off Key West (BROOKS and NIILER, 1975). No mean countercurrent occurs off Miami (LEE and MAYER, 1977) or Palm Beach (LEE *et al.*, 1985). Many past studies of the FC have been concerned with changes that take place on 2–15 day time scales due to onshore–offshore shifts (meanders) of the Florida Current axis (DUING, 1975; BROOKS, 1979) and atmospheric forcing (DUING *et al.*, 1977). Within the northern Straits of Florida, meandering motions have been associated with the generation of wind-forced continental shelf waves (SCHOTT and DUING, 1976; BROOKS and MOOERS, 1977a,b) and baroclinic instability (BOUDRA *et al.*, 1987, 1988). Approximately 25% of the combined velocity and temperature variance from moored current meter arrays in the northern Straits is explained by meandering of the current core, with dominant time scales in the 1–2 week period band (JOHNS and SCHOTT, 1988). Meanders were found to be characterized by an asymmetric or skewed waveform, with fluctuations leading on the eastern side of the Straits of Florida. Meander amplitudes at 27°N were found to be approximately 5 km r.m.s., and propagation speeds were downstream (northward) at 20–30 km day^{-1} with associated wavelengths of 150–350 km. Persistent upwelling (downwelling) has been found to occur over the western shelf and slope of the northern Straits of Florida in association with northward (southward) wind fluctuations (JOHNS and SCHOTT, 1988; LEE and WILLIAMS, 1988). Furthermore, the wind-driven velocity response was found to be strongly trapped over the continental shelf and upper slope. The annual cycle of FC volume transport was also shown to be significantly influenced by the annual cycle of meridional wind stress, i.e. a persistent northward wind component during the summer transport maximum shifting to a strong southward wind during the fall transport minimum (LEE and WILLIAMS, 1988; SCHOTT *et al.*, 1988).

In addition to horizontal meanders, the FC frequently forms cyclonic, cold-core frontal eddies in the Slope and Terrace waters. These disturbances were described by LEE (1975) and LEE and MAYER (1977) as small diameter (10–30 km) "spin-off" eddies which form along the western (cyclonic) edge of the FC and travel northward along the continental margin at speeds ranging from 20 to 50 cm s^{-1}. At these rates it usually takes 1–2 days for an eddy to pass a fixed point. Frontal eddies occur on the average of once per week and they have been observed to disturb the temperature field down to a depth of 200 m. They are recognized in the surface waters as warm, southward-oriented, tongue-like extrusions of the FC coupled to a trailing band of Shelf or Slope water. Frontal eddies evolve commensurate with enlarging offshore meanders of the FC front and appear to be part of the final growth stage of baroclinically unstable meanders (BOUDRA *et al.*, 1988).

Circulation in the eastern Gulf of Mexico is dominated by the Loop Current, the portion of the Gulf Stream which connects the Yucatan Current to the Florida Current (COCHRANE, 1973; NOWLIN and HUBERTZ, 1972). After penetrating the Gulf, the current pattern arcs anticyclonically to the east and southeast, forming a current "Loop" which subsequently exits through the Straits of Florida (Fig. 1). MAUL (1977) studied the annual cycle of the Loop Current between August 1972 and September 1973, and concluded that, although the pattern is cyclic, year-to-year variability is significant. MAUL (1977) showed a maximum penetration of the Loop to 28°45′N in August 1973, and a minimum of 24°15′N in December 1972. The detachment and westward movement of large, anticyclonic eddies from the Loop Current is well-documented (NOWLIN *et al.*, 1968; LEIPPER, 1970; LEIPPER *et al.*, 1972; MORRISON and NOWLIN, 1977; COCHRANE, 1972).

Frontal eddies and onshore–offshore meanders of the Loop Current have been observed to travel southward along the outer southwest Florida shelf on the time scale of

2–14 days (PALUSZKIEWICZ et al., 1983), similar to those observed in the northern Straits of Florida and southeast U.S. shelf (LEE and ATKINSON, 1983; ZANTOPP et al., 1987). STURGES and EVANS (1983) give evidence for a southward mean flow over the shelf for periods when the Loop Current is present at the shelf edge. VUKOVICH (1988) used satellite thermal imagery to conclude that a quasi-persistent cold perturbation exists where the southward flowing Loop Current turns eastward into the southern Straits of Florida. Presumably this cold perturbation signifies the existence of a cyclonic gyre at the entrance to the Straits of Florida off the Dry Tortugas.

Very little is known about the flow variability in the Southern Straits of Florida. The few studies that are available indicate the presence of a cold, cyclonic gyre over the Pourtales Terrace, a topographic feature that forms a 200–400 m platform off the lower and middle keys (Fig. 1) (BROOKS and NIILER, 1975; CHEW, 1974). BROOKS and NIILER (1975) made 16 dropsonde sections between Key West and Cuba from 3 May to 8 June 1972 and reported a persistent counterflow along the northern shore. They interpreted this flow as a cyclonic recirculation of FC water. We provide new information concerning this recirculation that indicates a preference for formation over the Pourtales Terrace and thus we name the circulation feature the "Pourtales gyre". We will discuss the gyre's spatial scales, structure, frequency and formation process. We also discuss the gyre's potential influence on retention of lobster and fish larvae spawned locally in the coastal and nearshore waters of the lower and middle Florida Keys, and on onshore transport of larvae from upstream remote source regions. Wind influence on coastal currents and potential transport of larvae are also discussed.

3. METHODS

Current and temperature variability in the study area were measured with a moored current meter array at the shelf edge and a near-bottom moored Acoustic Doppler Current Profiler (ADCP) on the Pourtales Terrace (Fig. 2). Water mass structures of the coastal zone and FC front were surveyed together with distributions of microzooplankton, and fish and lobster larvae on seasonal cruises. The moored array consisted of three moorings, each equipped with three Niskin Winged Current Meters (NWCM) at depths of 10, 17 and 27 m. Moorings were deployed along the shelf break (30 m depth) seaward of Carysfort Reef, Tennessee Reef and Looe Reef (Fig. 2) in April 1989. The current meters were exchanged by divers in August 1989 and again in November 1989, totaling about 1 year of observations from 10 April 1989–29 April 1991. A 150 kHz ADCP was deployed offshore of Looe Reef on the Pourtales Terrace at a depth of 215 m during the August cruise, and recovered in November. The ADCP transducers were positioned at 200 m. The transducer beam angle is 20° and the vertical resolution was set at 4.5 m (bin width), with 2 m blanking, which results in a vertical profile over 20 to 198 m. Wind data for the period of mooring deployments were obtained from the Key West airport. Current meter data were filtered with a 3 and 40 h low-pass (HLP) Lancoz filter and subsampled at 1 and 6 hourly intervals, respectively. Wind data were likewise 40 HLP filtered. Current vectors are rotated into an isobath coordinated system with v positive in the downstream direction and u positive offshore (Table 1).

Interdisciplinary seasonal cruises were conducted during spring (26 May–4 June 1989); summer (10–13 August); fall (7–11 November); and winter (5–9 February 1990). The three-dimensional physical property fields were mapped with a Sea Bird CTD and expendable bathythermographs (XBT), the distribution of microzooplankton, >25 μm, was determined using 30-l Niskin bottles attached to the CTD/rosette. Station locations are shown in Fig. 2. The sampling strategy was designed to resolve the water mass structures over the Pourtales Terrace from the outer reefs to the FC. A nine net MOCNESS sampler (YEUNG and MCGOWAN, 1991) with a 1 m^2 mouth and 0.333 mm mesh was towed at 0.5–1.5 m s^{-1} for the collection of fish and lobster larvae. Nitrate and phosphate levels were analysed with standard Technicon autoanalyser methods and chlorophyll concentrations were found by the methods of SMITH et al. (1981) for water samples of the fall and winter cruises. During the spring cruise all samples were taken simultaneously at the CTD stations. Subsequent cruises were split into two legs, with leg-1 consisting of the water mass and microzooplankton survey and leg-2 consisting of sampling for macrozooplankton and fish and lobster larvae using the same station pattern for both legs. It typically took 7–8 days to complete a cruise with 3–4 days required for each leg.

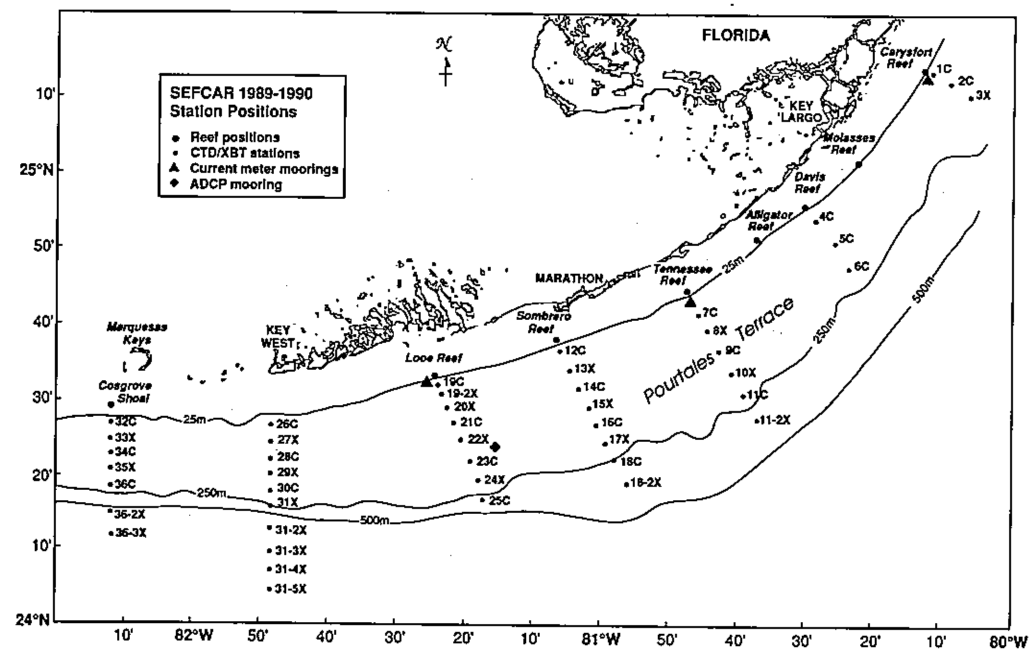

Fig. 2. Position of current moorings and hydrographic stations.

4. OBSERVATIONS

(a) *Hydrographic surveys*

The distribution of temperature at 100-m for each seasonal survey is shown in Fig. 3 together with station locations. A temperature of 20°C at 100-m is located within the sharp horizontal temperature gradient at this depth and can be used as an indicator of the western edge of the FC. This temperature, together with the strong horizontal temperature gradient, indicates that for the spring, summer and winter cruises the FC was in an onshore position at the northern two sections and was in an offshore position in the middle

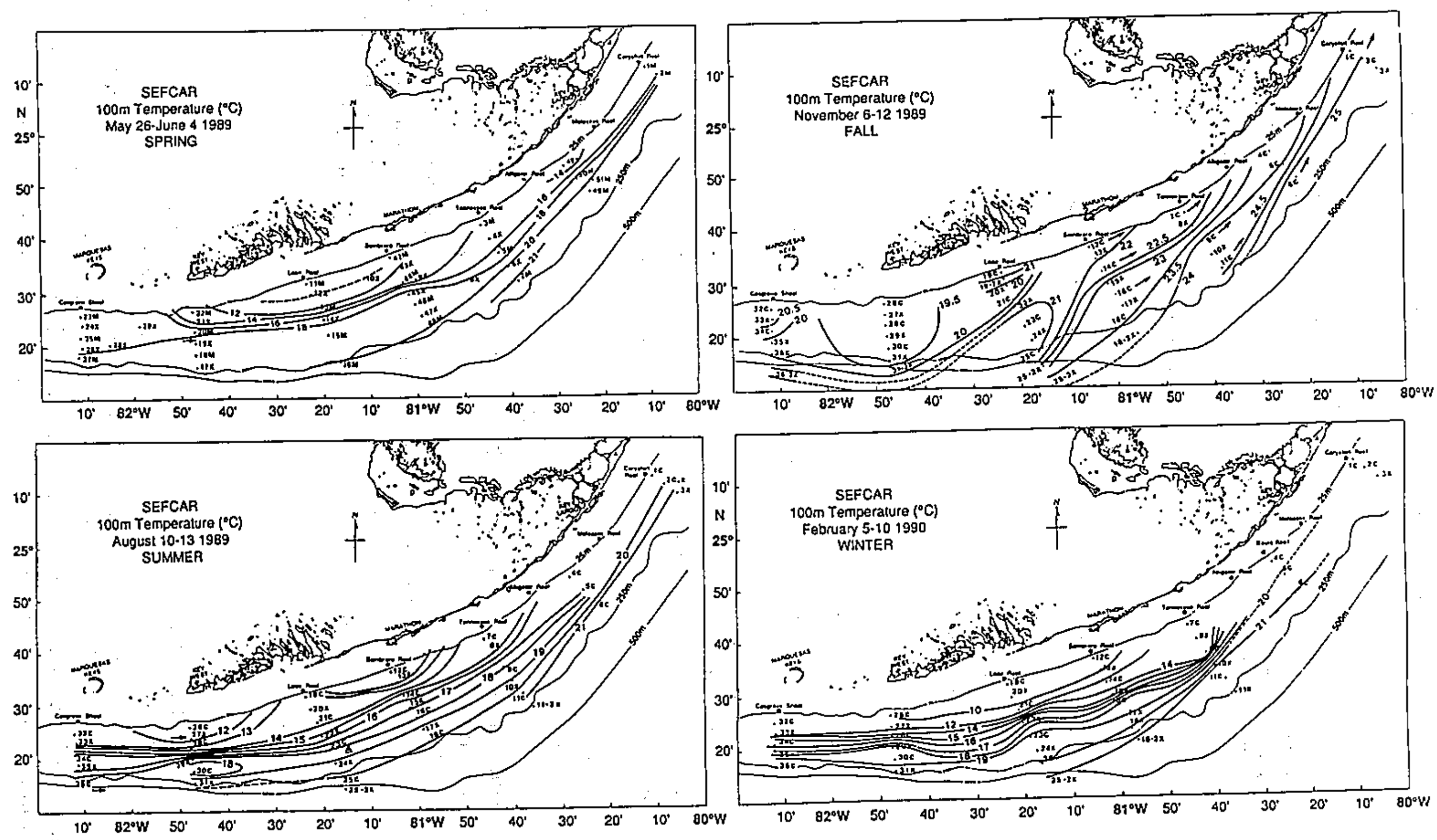

Fig. 3. Temperature at 100 m from seasonal hydrographic surveys. Arrows indicate current direction estimated from ship drift while on station.

Table 1(*a*). *First order statistics of* 40 *HLP time series and per cent of total variance due to the* 3 *and* 40 *HLP time series for the first deployment period of* 10 *April–*17 *August* 1990

Instrument I.D.	Instrument type	Water depth	Instrument depth		Start MM/DD/YY	End MM/DD/YY	Rot	Mean (40 HLP)	SD	Per cent variance (3 HLP)	Per cent variance (40 HLP)
C102	NWCM	30.0	17.0	U	04/10/89	08/17/89	28.0	−2.3	4.8	82.4	17.6
				V	04/10/89	08/17/89	28.0	24.3	22.7	69.0	31.0
				T	04/10/89	08/17/89		27.6	1.6	0.5	99.5
				S	04/10/89	08/17/89		38.4	1.2	0.2	99.8
T102	NWCM	30.0	17.0	U	04/10/89	08/17/89	61.0	1.1	3.7	68.1	31.9
				V	04/10/89	08/17/89	61.0	3.7	20.3	41.1	58.9
				T	04/10/89	08/17/89		27.9	1.6	1.5	98.5
				S	04/10/89	08/17/89		37.3	2.1	0.0	100.0
T103	NWCM	30.0	27.0	U	04/10/89	08/17/89	61.0	1.0	3.2	75.0	25.0
				V	04/10/89	08/17/89	61.0	2.4	13.4	49.5	50.5
				T	04/10/89	08/17/89		27.9	1.9	4.1	95.9
L101	NWCM	30.0	7.0	U	04/10/89	08/17/89	73.0	0.4	4.3	85.6	14.4
				V	04/10/89	08/17/89	73.0	2.6	19.7	45.9	54.1
				T	04/10/89	08/17/89		29.3	1.4	2.2	97.8
L102	NWCM	30.0	17.0	U	04/10/89	07/02/89	73.0	−0.9	5.4	65.9	34.1
				V	04/10/89	07/02/89	73.0	4.2	20.6	40.2	59.8
				T	04/10/89	07/02/89		26.9	1.3	4.5	95.5
				S	04/10/89	07/02/89		39.0	1.1	2.1	97.9
L103	NWCM	30.0	27.0	U	04/10/89	08/17/89	73.0	1.2	4.7	75.0	25.0
				V	04/10/89	08/17/09	73.0	1.1	13.0	55.2	44.8
				T	04/10/89	08/17/89		27.8	2.0	3.3	96.7

Per cent variance (40 HLP) = (Variance of 40 HLP data/Variance of 3 HLP data) × 100. Per cent variance (3–40 HLP) = 100 − per cent variance (40 HLP).

Table 1(*b*). *First order statistics of* 40 *HLP time series and per cent of total variance due to the* 3 *and* 40 *HLP time series for the second deployment period of* 23 *August–*6 *November* 1990

Instrument I.D.	Instrument type	Water depth	Instrument depth		Start MM/DD/YY	End MM/DD/YY	Rot	Mean (40 HLP)	SD	Per cent variance (3 HLP)	Per cent variance (40 HLP)
C201	NWCM MK 3	30.0	7.0	U	08/23/89	11/06/89	28.0	0.1	4.9	87.4	12.6
				V	08/23/89	11/06/89	28.0	15.3	24.7	52.2	47.8
				T	08/23/89	11/06/89		28.9	1.1	0.2	99.8
C202	NWCM MK 3	30.0	17.0	U	08/23/89	11/06/89	28.0	−0.4	4.5	87.8	12.2
				V	08/23/89	11/06/89	28.0	12.6	23.2	58.3	41.7
				T	08/23/89	11/06/89		28.1	1.1	0.4	99.6
C203	NWCM MK 1	30.0	27.0	U	08/23/89	11/06/89	28.0	0.5	7.0	81.5	18.5
				V	08/23/89	11/06/89	28.0	5.9	17.9	66.8	33.2
				T	08/23/89	11/06/89		30.0	1.0	3.4	96.6
T202	NWCM MK 3	30.0	17.0	U	08/23/89	11/06/89	61.0	1.0	5.3	55.9	44.1
				V	08/23/89	11/06/89	61.0	3.4	22.3	35.9	64.1
				T	08/23/89	11/06/89		28.9	1.3	0.3	99.7
L202	NWCM MK 3	30.0	17.0	U	08/23/89	09/03/89	73.0	0.1	2.0	90.2	9.8
				V	08/23/89	09/03/89	73.0	−0.3	9.9	82.8	17.2
				T	08/23/89	09/03/89		29.8	0.2	53.4	46.6
L203	NWCM MK 1	30.0	27.0	U	08/23/89	11/06/89	73.0	2.3	6.0	43.4	56.6
				V	08/23/89	11/06/89	73.0	3.8	17.2	14.7	85.3
				T	08/23/89	11/06/89		29.0	1.1	5.2	94.8

Per cent variance (40 HLP) = (Variance of 40 HLP data/Variance of 3 HLP data) × 100. Per cent variance (3–40 HLP) = 100 − per cent variance (40 HLP).

Table 1(*c*). *First order statistics of* 40 *HLP time series and per cent of total variance due to the* 3 *and* 40 *HLP time series for the third deployment period of* 7 *November* 1989–29 *April* 1990

Instrument I.D.	Instrument type	Water depth	Instrument depth		Start MM/DD/YY	End MM/DD/YY	Rot	Mean (40 HLP)	SD	Per cent variance (3 HLP)	Per cent variance (40 HLP)
C301	NWCM	30.0	7.0	U	11/07/89	02/26/90	28.0	−1.5	6.1	56.8	43.2
				V	11/07/89	02/26/90	28.0	20.7	27.1	45.6	54.4
				T	11/07/89	02/26/90		24.5	1.0	1.5	98.5
C302	NWCM	30.0	17.0	U	11/18/89	04/27/90	28.0	−1.7	5.7	63.0	37.0
				V	11/18/89	04/27/90	28.0	22.4	25.8	48.0	52.0
				T	11/07/89	04/27/90		24.6	0.9	1.8	98.2
T302	NWCM	30.0	17.0	U	11/08/89	02/05/90	61.0	0.9	4.4	47.5	52.5
				V	11/08/89	02/05/90	61.0	3.2	21.5	28.9	71.1
				T	11/08/89	02/05/90		24.5	1.2	0.9	99.1
T303	NWCM	30.0	27.0	U	11/08/89	04/28/90	61.0	1.9	7.7	49.7	50.3
				V	11/08/89	04/28/90	61.0	−2.9	18.9	32.7	67.3
				T	11/08/89	04/28/90		24.9	1.0	3.4	96.6
L301	NWCM	30.0	7.0	U	11/11/89	04/29/90	73.0	−1.0	6.0	60.6	39.4
				V	11/11/89	04/29/90	73.0	−0.9	23.6	24.6	75.4
				T	11/11/89	04/29/90		25.7	0.9	1.6	98.4
L303	NWCM	30.0	27.0	U	11/11/89	04/29/90	73.0	4.5	7.4	60.4	39.6
				V	11/11/89	04/29/90	73.0	−5.0	16.4	26.9	73.1
				T	11/11/89	04/29/90		24.8	1.0	3.5	96.5

Per cent variance (40 HLP) = (Variance of 40 HLP data/Variance of 3 HLP data) × 100. Per cent variance (3–40 HLP) = 100 − per cent variance (40 HLP).

sections, at Sombrero reef and Looe reef. This orientation generally matches the shape of the Pourtales Terrace, which is widest between Looe and Tennessee reefs as seen by the spreading of the 25 and 250 m isobaths. During the fall cruise the FC was in an onshore position at all sections north of Looe, judging from the strong, northeastward ship drift encountered while on station. Also, the 100 m temperature over the inner and middle part of the Pourtales Terrace was about 10°C warmer during fall than on the other cruises, again suggesting an onshore position of the warm FC at this time. The fall survey shows the FC front to shift abruptly offshore at the Looe section and cooler water was trapped against the slope at 100 m off Key West. During the spring, summer and winter cruises cold water of 10–13°C was found trapped against the slope in the middle part of the survey between Key West and Sombrero reef at the 100 m level. The only source for this cold water is upwelling from deeper layers of the FC. Historical data indicates that the 10 and 12°C isotherms intersect the bottom slope at mean depths of about 175 and 150 m, respectively, at sections offshore of Miami (LEE and MOOERS, 1977) and Key West (BROOKS and NIILER, 1975). Thus subsurface isotherm depths appear to be elevated over the Pourtales Terrace by as much as 50–75 m compared to the upstream and downstream regions, indicating enhanced upwelling.

Upwelling over the Pourtales Terrace could support a cyclonic circulation, which we will define as the Pourtales gyre. Evidence for the existence of this gyre can be found in contours of selected isotherm depths from the upper part of the thermocline (Fig. 4). A closed circulation appears present in the shoaling of the thermocline over the Pourtales Terrace during the spring and winter surveys. During the summer survey there was a narrow ridge of uplifted thermocline near the seaward edge of the Terrace that sloped downward across the Terrace toward the shelf edge, suggesting a broad, weak counter flow. There was no indication of gyre formation in the thermocline depths of the fall cruise, but there was an abrupt offshore shift of the FC front at the Looe sections (Fig. 3).

The Looe reef temperature sections for each survey are shown in Fig. 5. Uplifting of the thermocline is evident over the Terrace during the spring and winter cruises lending further support for cyclonic gyre structure. The cold 10–12°C water appears to be isolated against the bottom slope at the shoreward edge of the Terrace during these cruises. This cold pool extends 40–70 m higher up the slope during the spring and winter cruise compared to summer and fall. During the summer there is a general deepening of the surface mixed layer toward shore. During fall, isotherms deepened in an offshore direction, indicating northeastard flow over the Terrace.

The effect of gyre-induced upwelling over the Pourtales Terrace is clearly evident in nutrient concentrations from the Sombrero section for the fall and winter surveys (Fig. 6). During the fall cruises when the gyre was not present, nitrate and phosphate were near zero at 100 m (Fig. 6a). Whereas, when the gyre was well-developed during winter, the nutricline extended to 50 m over the terrace and 35 m at the shelf edge (Fig. 6b), and phosphate was observable throughout the surface mixed layer.

(b) *Currents*

Current and temperature measurements were made at the shoreward ends of the Carysfort, Tennessee and Looe sections from moorings maintained at the 30 m isobath with three rotations during a 1 year period from 8 April 1989–29 April 1990. Unfortunately complete records were not obtained at all sites due to instrument malfunctions. First order

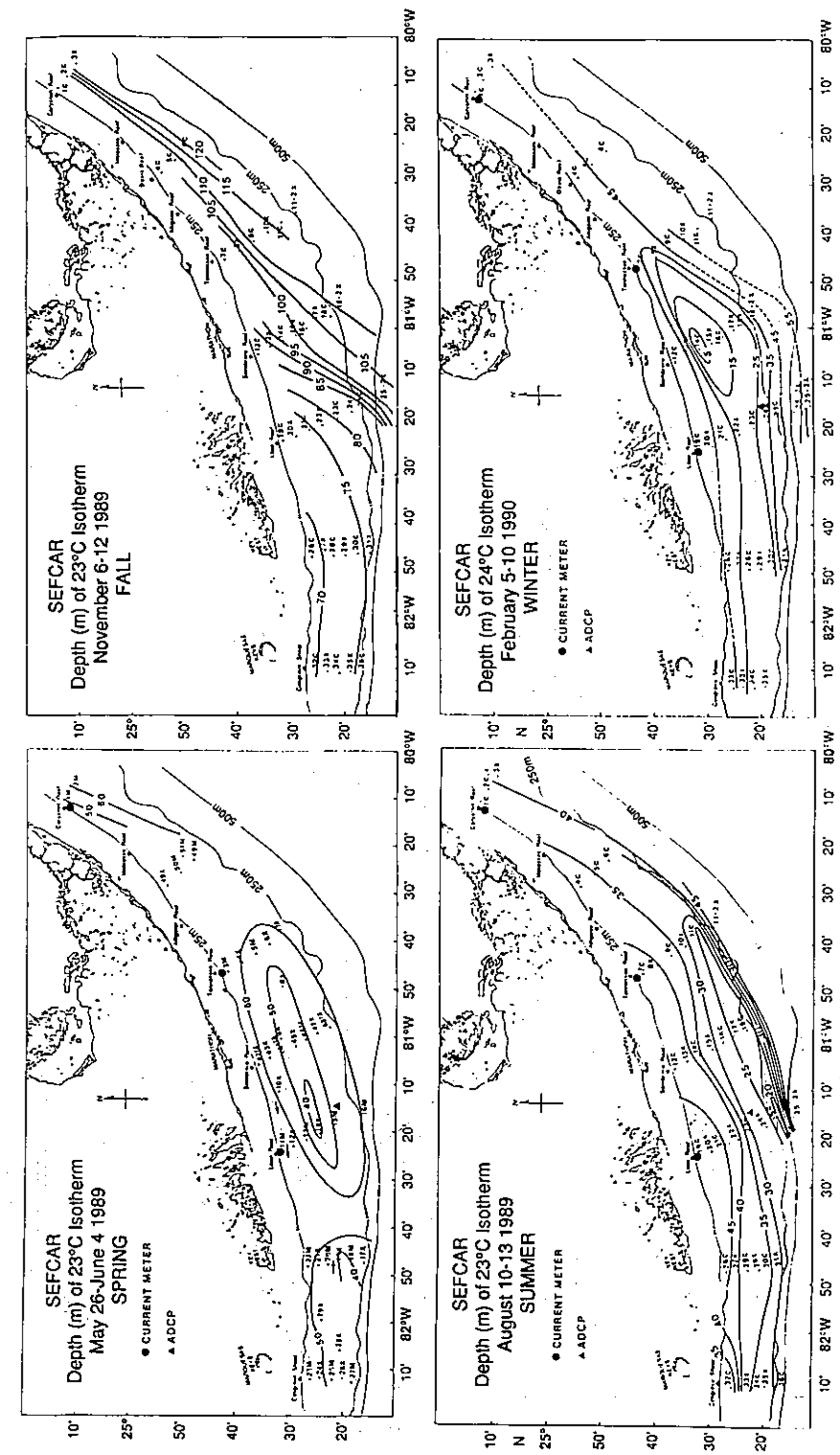

Fig. 4. Isotherm depths for upper part of the thermocline from seasonal hydrographic surveys.

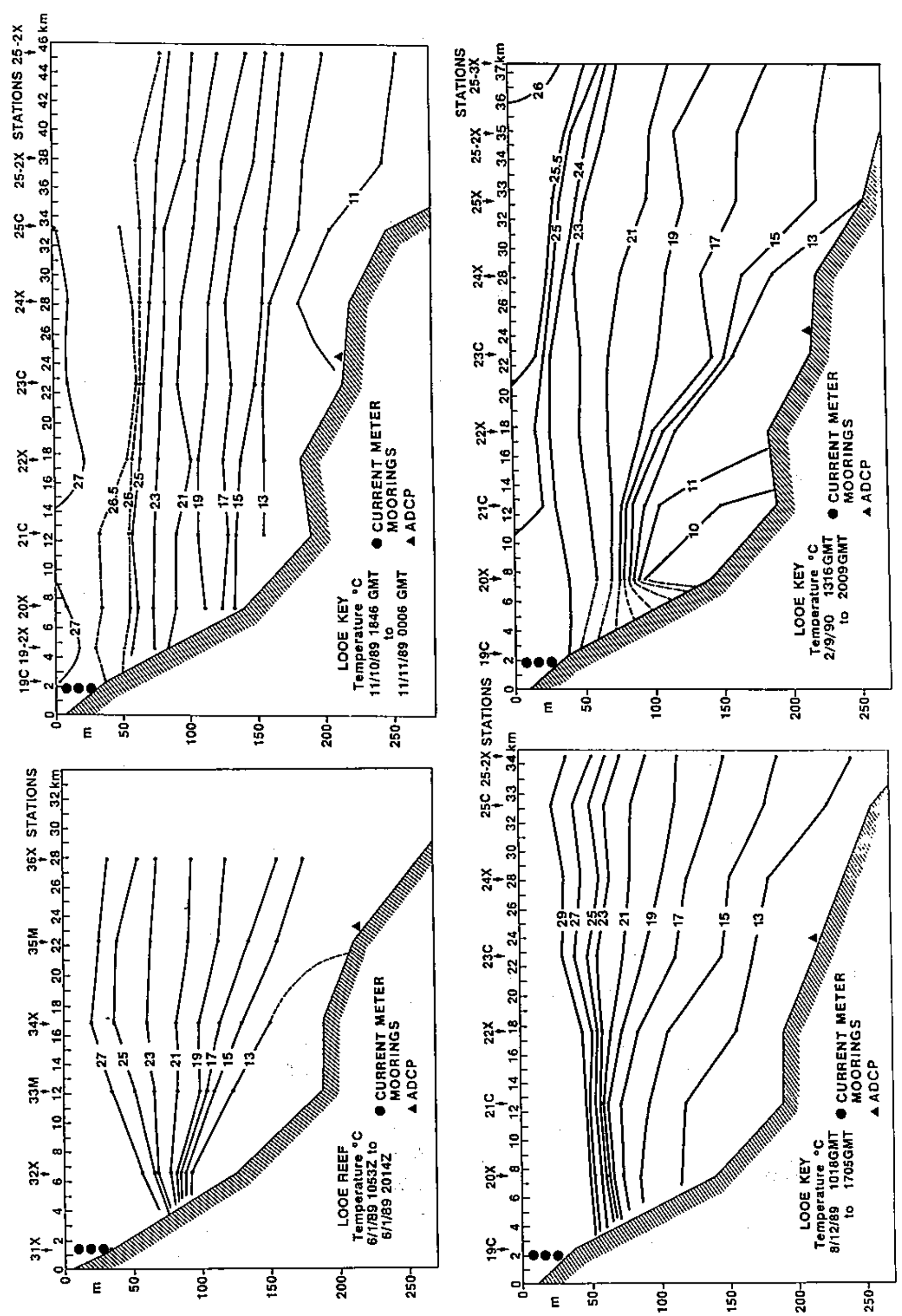

Fig. 5. Looe reef temperature sections from seasonal hydrographic surveys.

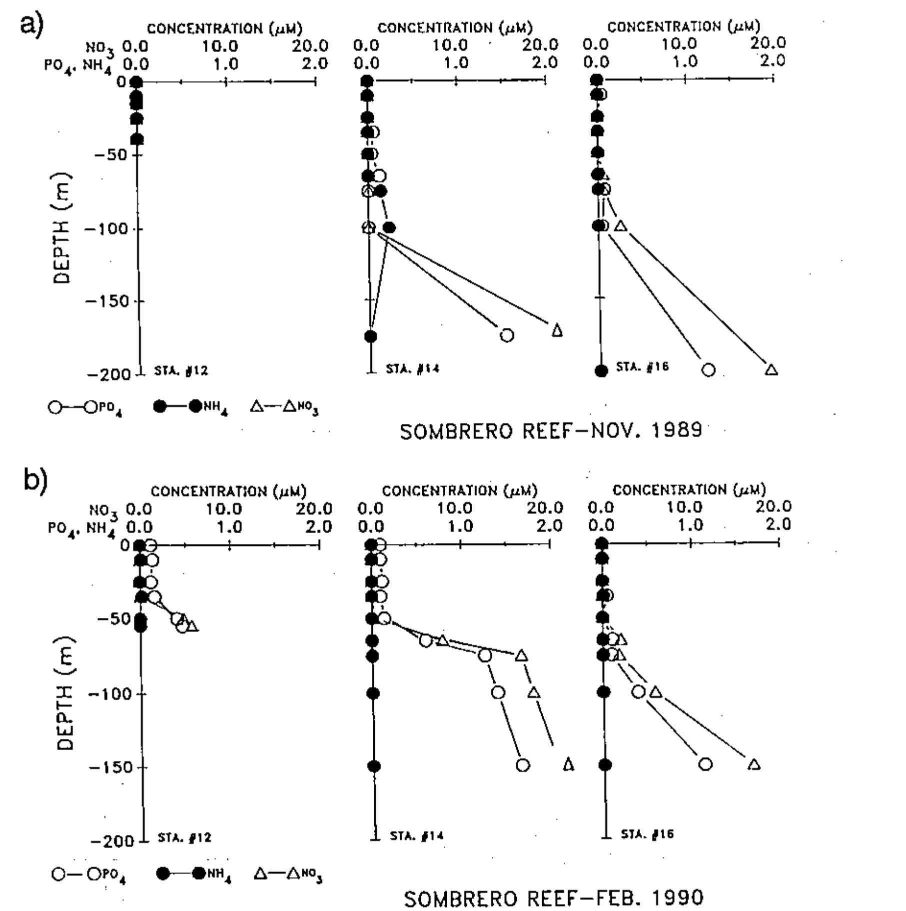

Fig. 6. Nutrient profiles at Sombrero Reef sections: (a) with no gyre present; (b) with gyre present.

statistics for the 3 and 40 HLP time series of alongshore and cross-shore velocity components and temperature are given in Tables 1a, b and c. The 3 HLP data contain fluctuations with periods of tidal and longer, whereas 40 HLP time series have tidal fluctuations removed by the filtering operation and represent subtidal or low-frequency variations.

Statistics of alongshore currents indicate that on the mean the FC front was located closer to the mooring site at Carysfort than at Tennessee or Looe sections. This results in the stronger northward mean flows at Carysfort that ranged from 13 to 24 cm s^{-1} at mid-depth for the three deployments, compared to less than 4 cm s^{-1} toward the northeast and east at Tennessee and Looe sites, respectively. Approximately 50–60% of the alongshore current variance is produced by subtidal motions at all sites, whereas cross-shore currents are dominated by tidal fluctuations with 70–85% of the total variance accounted for by tidal motions. The temperature variance was almost completely determined by low-frequency variations, which accounted for greater than 95% of the total

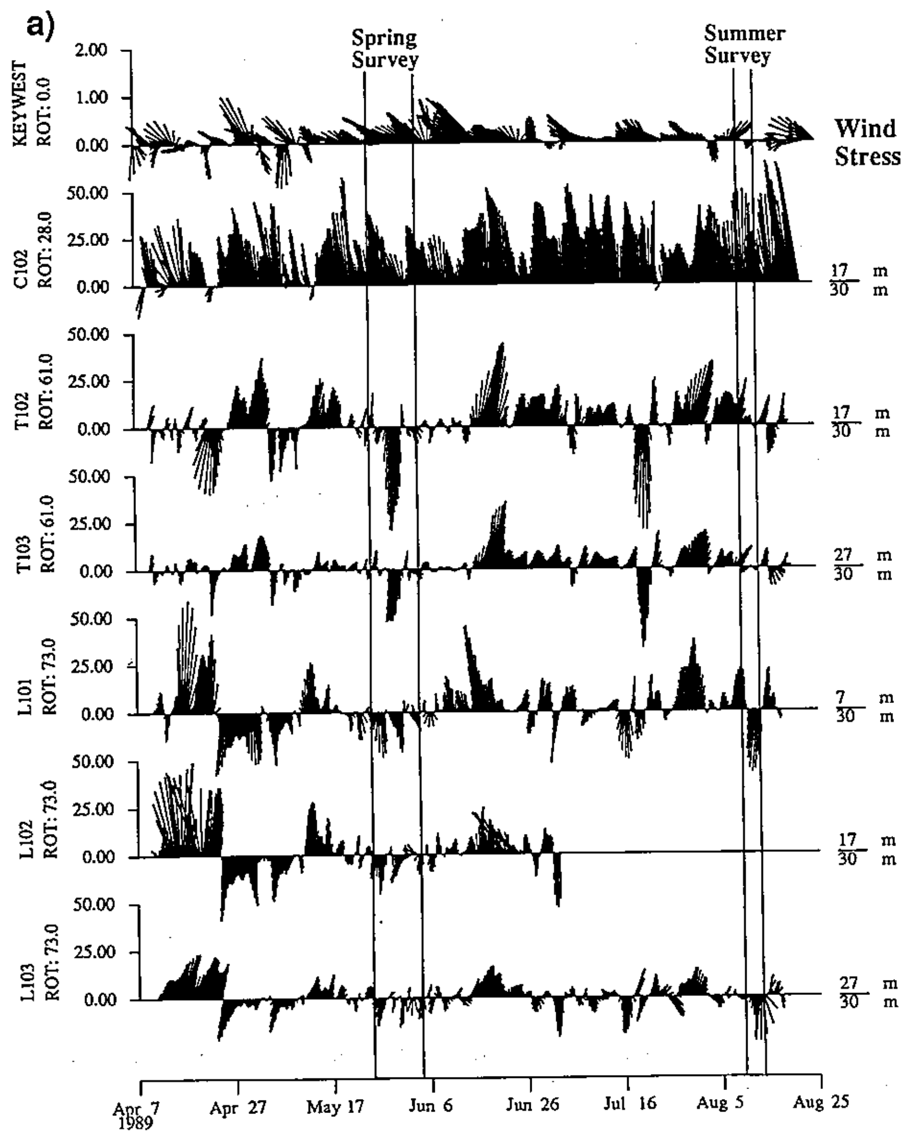

Fig. 7. (a) Vector time series of 40 HLP filtered currents (cm s^{-1}) and wind stress (dynes cm^{-2}), instrument depth and water depth at right, I.D. and rotation angle at left, winds are unrotated. 10 April–17 August 1989.

variance from all sites, and indicates that tidal motions and diurnal air temperature changes have little effect on water temperatures seaward of the reef.

Vector time series of subtidal currents are plotted with Key West wind stress vectors in Fig. 7a, b and c. Again, it is quite obvious from the strong, persistent northward flow off Carysfort that the FC front remains close to this site on most occasions. However, current reversals do occur and there are considerable low-frequency modulations of the magnitude of the northward flow that are most likely related to the northward passage of FC

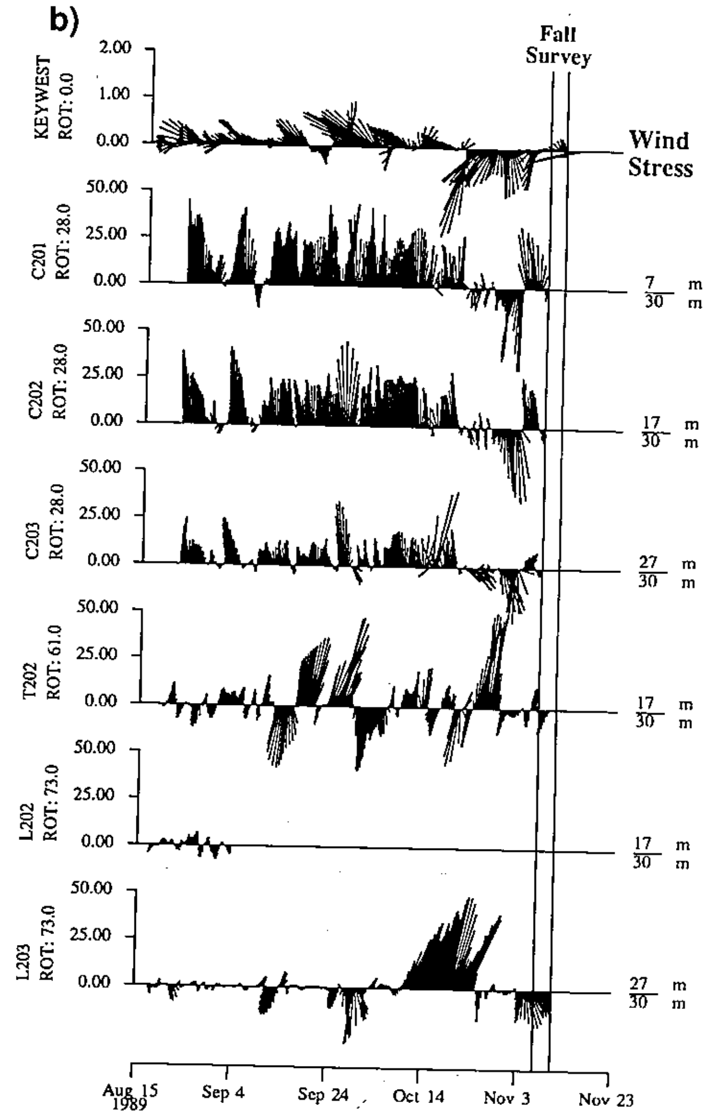

Fig. 7. (b) Vector time series of 40 HLP filtered currents (cm s^{-1}) and wind stress (dynes cm^{-2}), instrument depth and water depth at right, I.D. and rotation angle at left, winds are unrotated. 23 August–6 November 1989.

meanders and frontal eddies, similar to that found off Miami by LEE and MAYER (1977). Currents at the Looe site show a longer period variation than at the northern sites, with strong eastward and westward alongshore flow events lasting 2–3 weeks each. Subtidal current fluctuations appear to be barotropic at all sites, with current variations in phase and highly correlated throughout the water column. A significant decrease in current speed occurred near the bottom only, presumably due to bottom friction. Spatial coherence between currents at the different sites is generally weak. This is particularly true

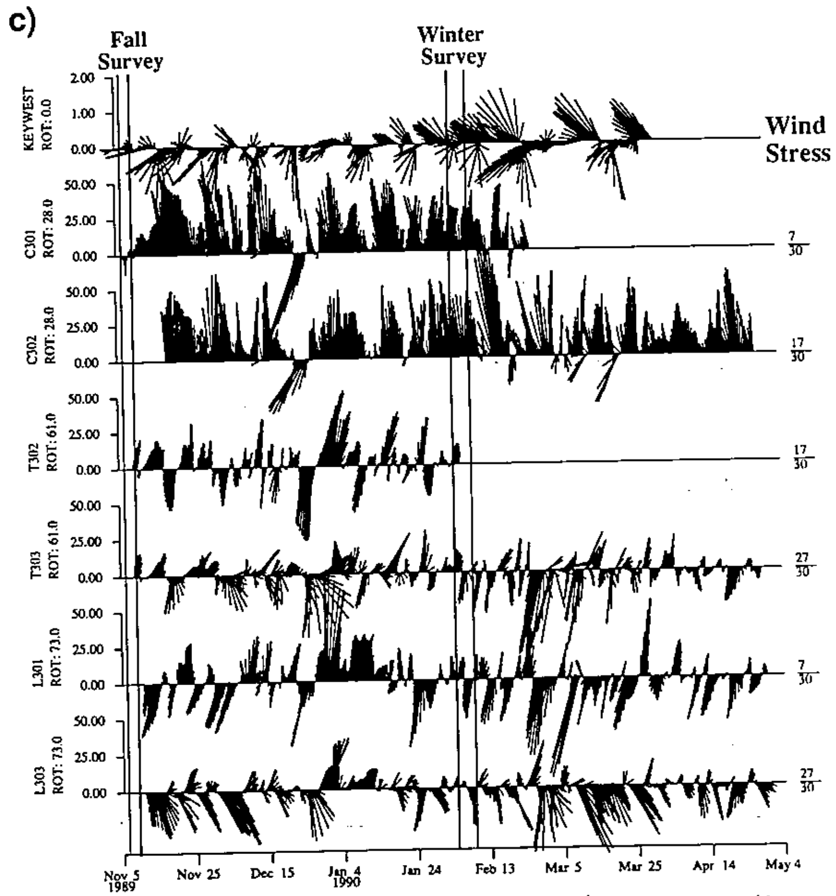

Fig. 7. (c) Vector time series of 40 HLP filtered currents (cm s^{-1}) and wind stress (dynes cm^{-2}), instrument depth and water depth at right, I.D. and rotation angle at left, winds are unrotated. 3 November 1989–29 April 1990.

for Carysfort compared to either Tennessee or Looe, but is also true between Tennessee and Looe sites, except for a few isolated events.

Energy spectra of year-long alongshore currents from each site are shown with alongshore wind stress at Key West in Fig. 8a and b. The current variance is spread over a wide band from 21 to 80 days at Carysfort and becomes selectively grouped at periods of 4, 7 and 20 days at Tennessee, and occurs in two broad bands of 3–10 and 30–50 days at Looe. Alongshore current fluctuations in the 3–10 day band at Looe are coherent with the local Key West alongshore wind stress with a phase lag of about 12 h (Fig. 8b). This response time is typical of wind forced barotropic response times observed at other shelf locations in similar water depths (Lee *et al.*, 1989)..

Current fluctuations within the 30–50 day period band at Looe appear to be related to long period shifts in the onshore/offshore position of the FC front. When the front is

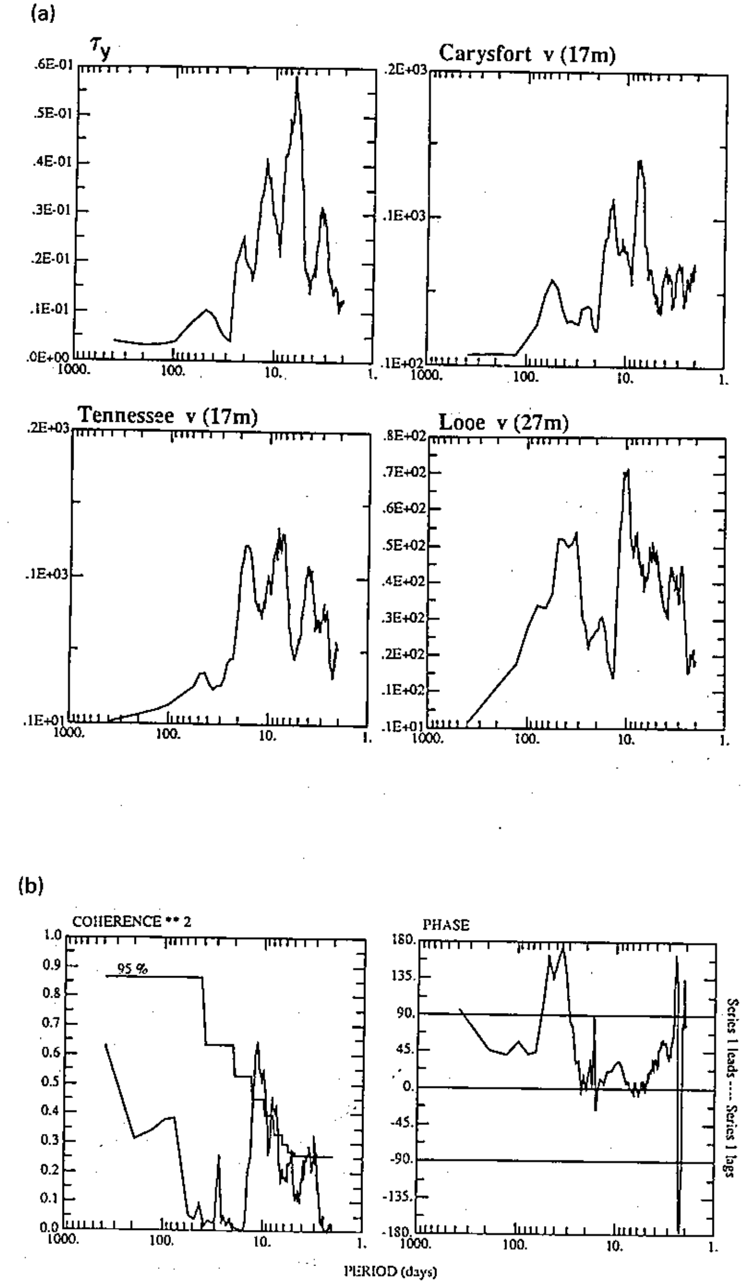

Fig. 8. (a) Variance conserving energy spectra for Key West wind stress (τ_y), and alongshore currents at each mooring, for 1 year period from 4 October 1989–4 January 1990. (b) Coherence square and phase between Key West wind stress and alongshore currents at Looe mooring site for 1 year period from 10 April 1989–1 April 1990.

located in an onshore position, strong eastward alongshore flows occur at the Looe site. When the FC front is in an offshore position, i.e. near or offshore of the seaward edge of the Pourtales Terrace, a cold cyclonic gyre is formed. The current meter data substantiate that westward flow occurred on the shoreward side of the gyre during the hydrographic surveys when the gyre circulation could be inferred from the temperature fields (Figs 3, 4 and 7). These long-period westward flow events and the strong eastward flow events do not appear to be related to local winds.

An Acoustic Doppler Current Profiler (ADCP) was deployed at 200 m on the 215 m isobath along the Looe Reef section for the August to November measurement period. This position is approximately 25 km seaward of the Looe Reef current meter mooring (Fig. 2). The east–west current components computed in 4.5 m vertical bins show a 2 month period fluctuation, with maximum eastward flows of 150–200 cm s^{-1} occurring around the end of August and end of October and a current reversal near the end of September that produced westward flow over the total water column (Fig. 9). The westward flow was intensified near the bottom, reaching speeds of 40 cm s^{-1}.

The ADCP record can be used as an indicator of the onshore–offshore movement of the FC front. At times of strong eastward flow the front would be located near or shoreward of the ADCP site, and during westward flow or weak eastward flow the front would be located further offshore. The summer hydrographic survey was conducted at a time when the FC front was located at the seaward edge of the Pourtales Terrace at the Looe section (Fig. 3) and moving onshore across the Terrace and toward the ADCP site, as shown by the increasing eastward currents at the ADCP (Fig. 9). The temperature section shows isotherms sloping downward toward shore, indicating westward flow over the shelf and Terrace shoreward of the ADCP (Fig. 5), which is substantiated by the current records from the Looe mooring (Figs 7b and 9). Currents were weak at the Looe site from 15 August to 24 September and indicate that the shoreward movement of the FC front did not extend much past the ADCP site. There was no survey during the current reversal at the ADCP site at the end of September, but strong westward flow also occurred at the Looe mooring site (Figs 7b and 9) that was in phase with the ADCP flow reversal and indicates a large-scale westward flow event, presumably from the spin-up of the Pourtales Gyre. During October the FC front appears to have moved across the Terrace to a position close to the Looe site, resulting in strong eastward flow at both Looe and ADCP sites (Fig. 9). A strong southward wind event was occurring at the same time (typical of fall wind events) and appeared to have no effect on the observed currents at the Looe section (Fig. 7b), where this wind direction is offshore, but had considerable effect on the current at Carysfort where this wind direction is alongshore.

The fall survey (Figs 3 and 4) appears to have been conducted during an offshore shift of the FC front, coupled to the formation of the Pourtales Gyre, judging from the decreasing eastward current speeds at the ADCP site, strong westward flow observed at Looe (Fig. 9), and the onshore–offshore orientation of the FC front at 100 m just southeast of the ADCP site (Fig. 3). The westward flow at Looe lasted for about 20 days during a period of weak and variable winds (Fig. 9). Westward flow was also observed at the Looe mooring during the spring and winter surveys when the hydrographic data indicate that the gyre was well developed (Fig. 7a and c). Current variability at the Tennessee Reef site appears to represent a transition region from the FC dominated strong downstream flows that characterize the Carysfort site to the longer period Gyre/meander regime at Looe.

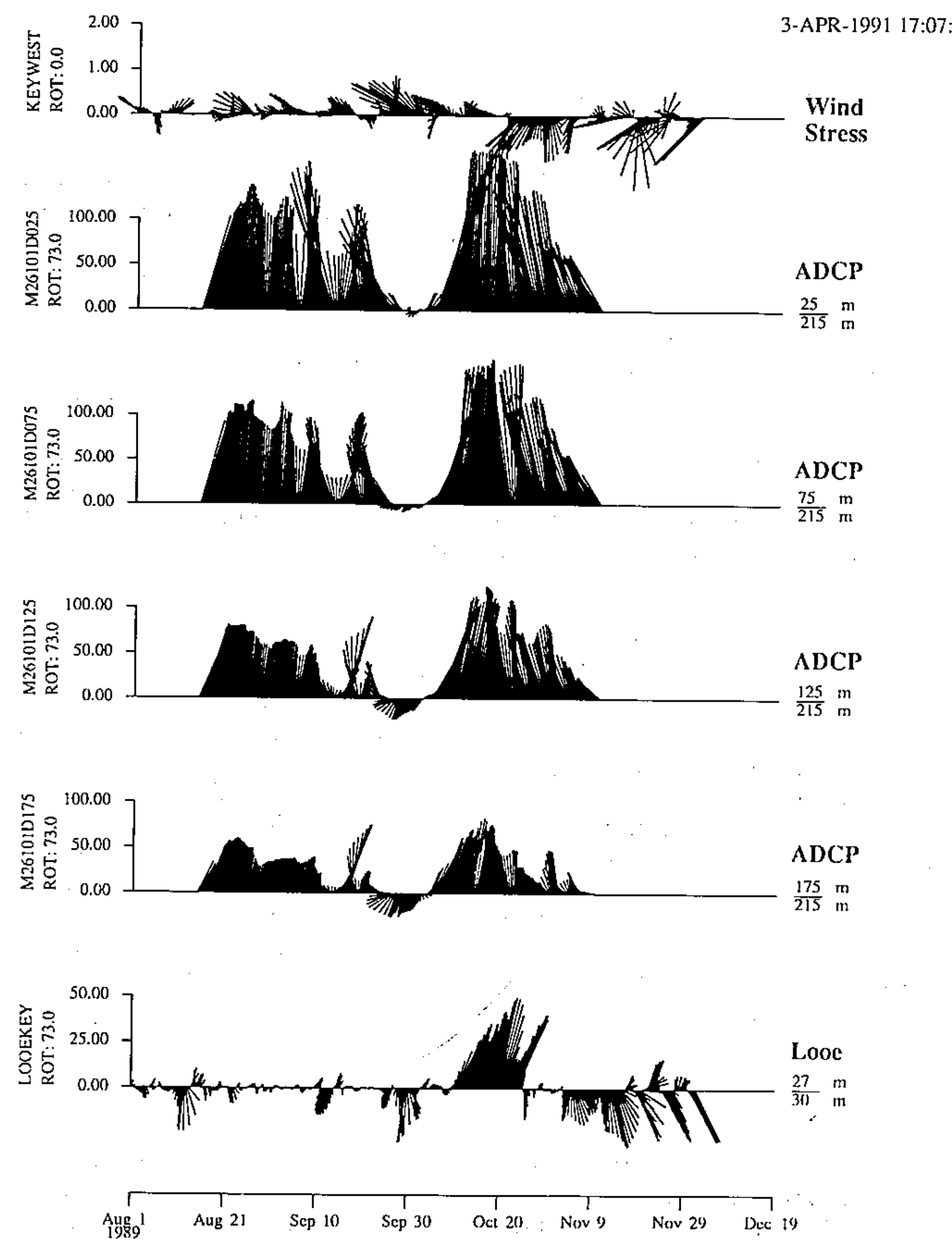

Fig. 9. Vector time series of 40 HLP filtered currents (cm s^{-1}) from the ADCP and Looe mooring (both rotated 73°) and Key West wind stress unrotated (dyne cm^{-2}).

5. DISCUSSION

(a) *Pourtales Gyre*

Both the hydrographic surveys and moored current measurements indicate the presence of a cold cyclonic gyre located coincident with the topography of the Pourtales Terrace (Figs 3–7). Current meter and ADCP data on the Looe section indicate that the period of gyre formation ranges from 1 to 2 months (Figs 8 and 9) and that westward flow, which occurs on the north side of the gyre can last 1–3 weeks with speeds of 20–50 cm s^{-1} (Figs 7 and 9). Seasonal hydrographic surveys indicate some presence of a gyre on all four cruises (Figs 3 and 4). The gyre appeared to be best developed in the spring and winter surveys, where closed, cyclonic circulations were indicated in the thermocline over the Pourtales Terrace (Fig. 4) and upwelling of cold, fresh nutrient rich waters from deeper layers of the FC was found trapped against the slope (Figs 3 and 5). Local winds during these surveys were mostly toward the west, which is downwelling favorable for the coastal waters of the southern keys. The spring survey shows a cold, cyclonic gyre over the Pourtales Terrace between Key West and Key Largo. Gyre dimensions are approximately 100 × 40 km, with the major axis following the alignment of the Pourtales Terrace. The cold core of the gyre was centered about 17 km offshore of the shelf break between Looe and Sombrero Reefs with westward flow north of the center and eastward flow south of the center. The winter survey shows the gyre center located about 13 km seaward of the Sombrero Light, and dimensions were approximately 75 × 40 km.

Formations of the gyre appears to be related to the onshore–offshore position of the FC and not to local wind forcing. Thus the gyre formation may be tied to instabilities of the FC front, which can cause offshore shifts of the front (offshore meanders) that propagate downstream with the mean flow. The coincidence of gyre formation over the Pourtales Terrace suggests a trapping mechanism and generation of localized upwelling over the Terrace which can be due to either: (1) upwelling from divergent flow over the Terrace as the FC is steered offshore by topography; or (2) cyclonic curvature of the Straits of Florida, which forces cyclonic curvature of the FC flow and upwelling in the trough. Most likely both processes act together to produce the observed 20 m uplifting of the thermocline over the center of the Terrace (Figs 4 and 5) and trapping of cold waters against the base of the slope (Figs 3 and 4) in spite of persistent downwelling favorable winds.

The relative influence of cyclonic flow curvature on maintaining a cyclonic gyre due to turning of the FC around the lower Florida Keys can be estimated with use of the cross-stream momentum equation for continuously stratified flow written in natural coordinates (GILL, 1982):

$$U^2/R + fU = -(1/\rho)\,\mathrm{d}p/\mathrm{d}n \qquad (1)$$

where U is the downstream fluid velocity, n is the direction perpendicular to the fluid path, p is pressure, ρ is the fluid density and R is the radius of curvature. The curvature term is represented by U^2/R and its magnitude is compared to the Coriolus term fU for a downstream flow of 100 cm s^{-1} and a radius of curvature of 100 km, which represents the curvature of the Straits of Florida at the location of Looe and Sombrero Reefs. Using these values the curvature term accounts for approximately 20% of the momentum balance. This means that the downstream flow is not in geostrophic balance in this area. Therefore, the cross-stream pressure gradient must increase to balance the added influence of the flow curvature, which results in onshore flow in the bottom boundary layer and upwelling that can support the formation of the Pourtales gyre.

A similar effect of flow curvature and formation of a persistent cyclonic gyre should also occur at the western entrance to the southern Straits of Florida where the southward flowing Loop Current turns abruptly to the east. Indeed, VUKOVICH (1988) has shown compelling evidence from satellite derived AVHRR thermal imagery and hydrographic data for the persistence of an elongated cold perturbation of the FC front off the Dry Tortugas.

Upwelling in the center of the gyre and along the continental slope lifts the thermocline into the euphotic zone where nutrients are available for planktonic uptake. Upwelling velocities (w) in the cold core can be estimated from conservation of relative vorticity (ζ). Following ARTHUR (1965) the conservation of relative vorticity in natural coordinates is:

$$f\,\mathrm{d}w/\mathrm{d}z = \mathrm{d}\zeta/\mathrm{d}t + \beta V \qquad (2)$$

where $\zeta = V/R - \mathrm{d}V/\mathrm{d}n$, and β is the change in planetary vorticity (f) with latitude; $\beta = 2 \times 10^{-13}\ \mathrm{cm}^{-1}\,\mathrm{s}^{-1}$. Assuming a uniform flow V which tends to follow the isotherm depth pattern of the spring survey (Fig. 4) with cyclonic flow curvature of radius R around the uplifted thermocline, then the vertical velocity at depth h can be estimated by:

$$w_h = -(h/f)(\mathrm{d}\zeta/\mathrm{d}t) - h\beta V/f. \qquad (3)$$

The tangential velocity V is assumed equal to the westward flow observed at the Looe current mooring during the event of approximately 25 cm s^{-1}. The radius of curvature R at the eastern side of the feature is estimated at 50 km and on the northern side R is assumed very large where the flow is mostly westward and curvature is small, thus $\zeta = 0$ on the northern side and $\mathrm{d}\zeta/\mathrm{d}t = -0.3 \times 10^{-10}\ \mathrm{s}^{-2}$, which represents the time rate of change of relative vorticity as a water parcel travels around the eastern end of the gyre, assuming $\mathrm{d}V/\mathrm{d}n = 0$. The vertical velocity at 50 m can then be estimated from (3) as $W_{50\,\mathrm{m}} = 2 \times 10^{-3}\ \mathrm{cm\,s}^{-1}$. The strength of the vertical velocity depends primarily on the change in curvature vorticity along a streamline. The curvature is cyclonic around the uplifted thermocline of the gyre which gives a positive (upwelling) vertical velocity. The strength of the upwelling velocity is about 0.002 cm s^{-1}, or about 2 m per day.

(b) *Wind influence*

Local winds over the southern Straits of Florida are primarily from the southeast due to the persistence of the Azores–Bermuda atmospheric high (Fig. 7a, b and c). Southeast winds are most persistent in the summer months of June–August, when the atmospheric high is strongest (Fig. 7a). During fall (September–November) a high pressure system develops over the southeastern coastal states that can produce strong southward wind events that are coherent over the Straits of Florida for periods of 5–10 days. The October southward wind event shown in Fig. 7b is a typical example. These fall wind events are primarily responsible for the seasonal minimum of FC transport observed in the northern Straits (LEE and WILLIAMS, 1988). During winter (December–February) and spring (March–May) cold fronts extend southward across the southern Straits with an average period of about 6 days, causing an increase in wind speeds and a clockwise rotation in direction (Fig. 7c), and the most energetic peak in the meridional wind stress spectra (Fig. 8b).

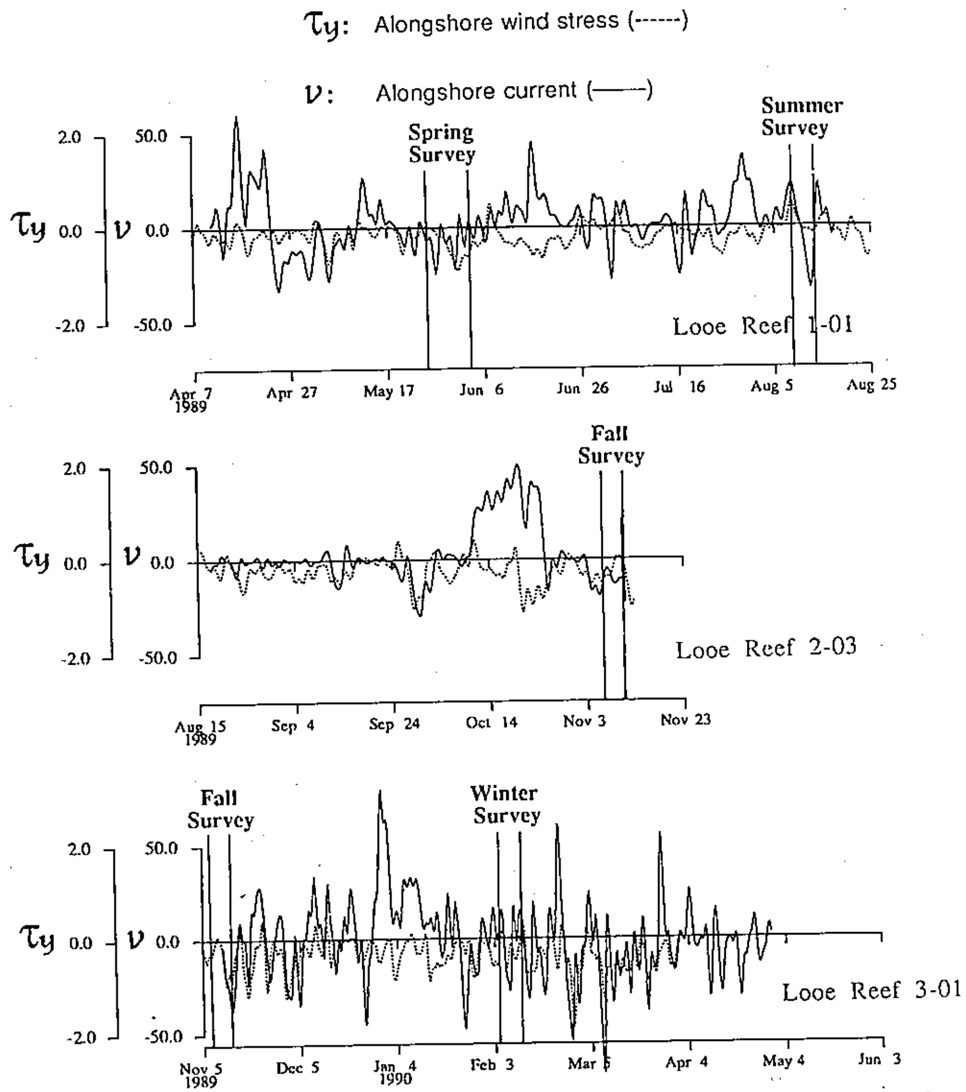

Fig. 10. Alongshore flow at Looe mooring (cm s^{-1}) and alongshore wind stress (dynes cm^{-2}) from Key West, both rotated 73°, for 1 year period, 10 April 1989–1 April 1990.

The alongshore component of the Key West wind stress and currents at each measurement site are plotted together in Fig. 10. At times the currents are strongly correlated with the winds (first week in May, second week in August, last week in September and during many of the winter cold front events), and at other times the wind has no bearing on the current (mid-April, mid-June, mid-October in 1989, and early January 1990), apparently when the FC influence is dominant. Spectra of the full year of currents from the lower layer at the Looe site show well defined energy peaks at periods of 30–50 days and

3–10 days (Fig. 8b). The 30–50 day period is not coherent with the alongshore wind and was explained previously as resulting from long-period meandering of the FC and formation of the Pourtales gyre. Current fluctuations in the 3–10 day band are strongly coherent with Key West alongshore winds with a lag of about 12 h.

Current meter records from Carysfort and Tennessee reef had weak coherence with alongshore winds. Analysis of year-long coastal sea level records from Key West (not shown) also did not reveal any significant coherence with either Key West winds or Looe currents, unlike the situation one typically finds for the local wind forced response in a coastal ocean with a straight coastline (CSANADY, 1982). The orientation of the Straits of Florida changes from east–west to north–south between Key West and Key Largo, which means that alongshore wind forcing will only be significant in the lower keys between Key West and Marathon for the prevailing southeast winds. Therefore, the Looe reef site is the only location in the moored array where significant wind driven alongshore flows are to be expected. Local winds at the Tennessee and Carysfort sites are primarily cross-shore, which will not result in significant current response in the absence of the coastal constraint (CSANADY, 1982).

The combined effect of the seaward flowing FC in the southern Straits, with westward flow nearshore when the Pourtales Gyre is well-developed, can have a profound influence on wind stress and Ekman transports for the prevailing westward winds. The magnitude of the east–west component of the wind stress is given by:

$$\tau_x = \rho_a C_d (U - u)^2 \quad (4)$$

where ρ_a is the density of air, $C_d = 1.5 \times 10^{-3}$ is the drag coefficient, and U and u are the east–west components of the wind and current velocities. For a typical westward wind speed of 6 m s^{-1} against the FC eastward speed of 1.5 m s^{-1} gives $\tau_x = -60\ m^2\ s^{-2}$, whereas on the northern side of the Pourtales Gyre the current is toward the west same as the wind at a speed of about 0.5 m s^{-1}, which gives for the wind stress $\tau_x = -30\ m^2\ s^{-2}$. Therefore for the same wind, the wind stress is a factor 2 larger near the FC axis compared to the region of westward flow on the northern side of the gyre. The Ekman transport, $T_E = \tau/f$ is also two times greater at the FC axis compared to the westward flow region of the gyre. This will result in a northward convergence of surface Ekman transport into the gyre and across the Pourtales Terrace to the coastal boundary, where downwelling should occur over the steep continental slope. Ekman convergence and downwelling is indicated in the Looe temperature sections by deepening of the mixed layer and strengthening of the thermocline over the continental slope (Fig. 5). Repeated temperature sections (not shown) were made at Looe during the spring survey when the Pourtales gyre was well-developed and westward wind strength doubled. The sections were made over a 4 day period from 28 May to 1 June and show a 40 m depression of the 27°C isotherm where it intersects the bottom slope at depths of 30 and 70 m, respectively. This occurred during a period when the westward wind speed increased from about 5–10 m s^{-1}. Assuming that the thickening of the mixed layer and deepening of the thermocline were due solely to the increased westward winds gives a downwelling velocity along the slope of about 10 m per day. This downwelling velocity is quite large for a 10 m s^{-1} wind with no eddy features present and gives further support that the enhanced surface Ekman convergence due to the presence of the cyclonic gyre and offshore FC jet could account for the increased downwelling.

(c) *Implications for coastal ecosystems and transport of larvae*

Variability of currents and water mass structure in the Florida Keys coastal waters is dominated by FC meanders and eddies, and circulation due to local wind forcing. We believe that these processes combine to strongly influence nutrient and plankton distributions, as well as concentrations and recruitment patterns of fish and lobster larvae, which lead us to the following conceptual model. Upwelling in the Pourtales Gyre causes an elevation of the FC nutricline into the euphotic zone over the Pourtales Terrace (Fig. 6a and b) and subsequent increases in chlorophyll and zooplankton concentrations (chlorophyll and nauplii distributions north of the winter gyre, Fig. 11a, compared to concentrations within the gyre wake, Fig. 11b). The combination of onshore surface Ekman transport convergence and cyclonic circulation in the Pourtales Gyre should result in the concentration of passive planktonic drifters in the northwest quadrant of the gyre and along the western side as shown schematically in Fig. 12a and b, superimposed on the isotherm depth field of the spring survey and on the temperature section off Looe during this survey. Both the gyre cyclonic circulation and onshore surface Ekman transports will advect larvae into the coastal boundary in the northern part of the gyre. Concentration of larvae in the surface mixed layer on the shoreward side of the gyre will result due to trapping between the shallow coastal boundary and the stable thermocline. Higher production should occur at this location due to intrusion of new nutrients into the euphotic zone associated with gyre induced upwelling (Fig. 11b). Bands of increased concentrations of larvae may also extend around the southern end of the gyre within the cyclonic circulation and to the west along the coastal boundary due to westward wind driven flows.

Distributions of larval slipper lobsters (genus *Scyllarus*) determined from the MOCNESS tows generally agree with the above conceptual model. *Scyllarus* spp. of all developmental stages were more abundant along the shoreward side of the spring gyre, where they were concentrated in the vicinity of the thermocline and bottom slope intersection (Fig. 13a and b). Copepod nauplii, which constitute a significant part of the diet of many species of larval fish show a similar distribution that appears controlled by the gyre dynamics, i.e. greater concentrations within the gyre with greatest abundance on the shoreward side (Figs 14a and 11b). When the gyre is not present both concentrations of phyllosoma larvae and abundance of copepod nauplii tend to be lower and more evenly spread out across the coastal zone (Figs 14b and 11a). Seasonal changes in abundance do not appear to influence the observed larval patterns for similar patterns were found in both spring and winter surveys when the gyre was present. A seasonal effect should be more widespread than the mesoscale gyre scale. The abundance of copepod nauplii within the gyre structure indicates a highly favorable food environment for fish larvae. Therefore survival of fish larvae and successful recruitment may be enhanced in this region. Diets of phyllosoma larvae are not well known, but if small zooplankton are an important component of their food, then their survival will also be enhanced by the gyre structure.

The Pourtales Gyre circulation and surface Ekman drift act together to transport planktonic species carried by the FC shoreward for recruitment into the lower Keys. Therefore spiny lobster larvae, *Panulirus*, which have long planktonic stages of 6–12 months (LEWIS, 1951; SIMS and INGLE, 1966), could be recruited from remote Caribbean or South American locations. The combination of the gyre circulation with the westward wind driven coastal flow provides a transport and retention mechanism for local recruitment of fish larvae spawned in the coastal or offshore waters of the lower Keys. The

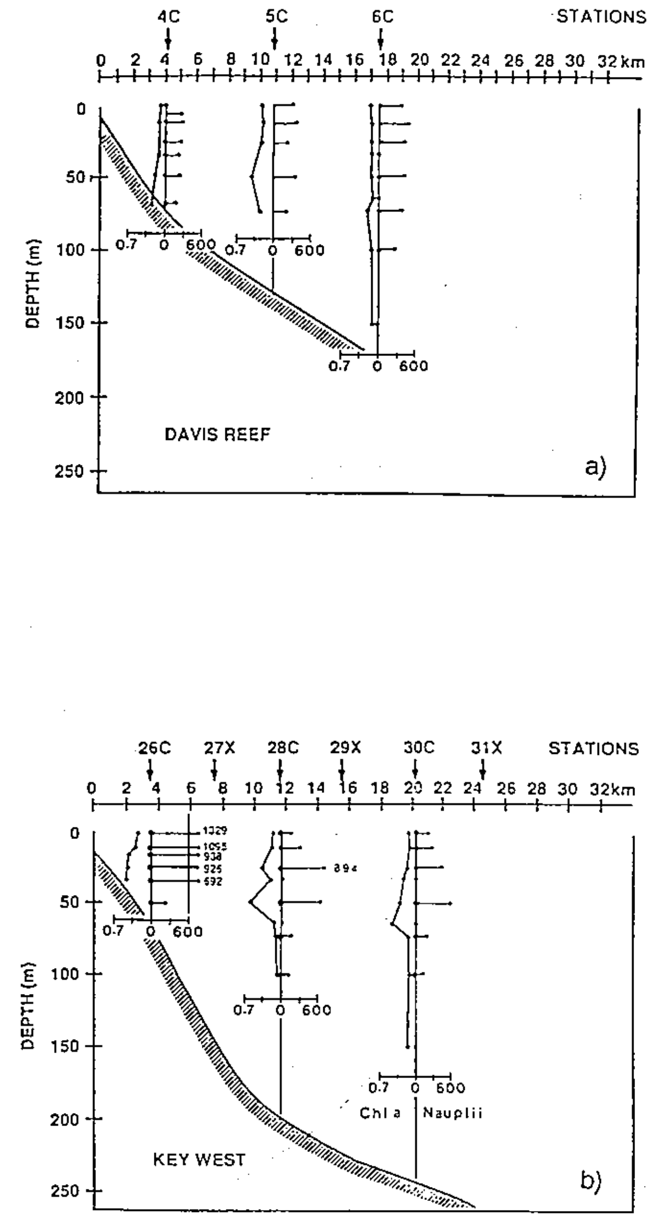

Fig. 11. (a) Chlorophyll *a* (on left, $\mu g\, l^{-1}$) and microzooplankton (Nauplii/30 l) profiles (on right) north of the Pourtales gyre during the winter survey. (b) Chlorophyll (on left) and microzooplankton (Nauplii) profiles (on right) across the Pourtales Gyre upwelling wake during the winter survey.

retention time for larvae that circuit the Pourtales Gyre would be about 13 days for an average drift speed of 20 cm s^{-1} and a circumference of 220 km (Fig. 15). The planktonic stage of the slipper lobster, *Scyllarus* (ROBERTSON, 1968), as well as grouper and snapper larvae (LEIS, 1987) can last for at least 1 month. Therefore it would take two–three

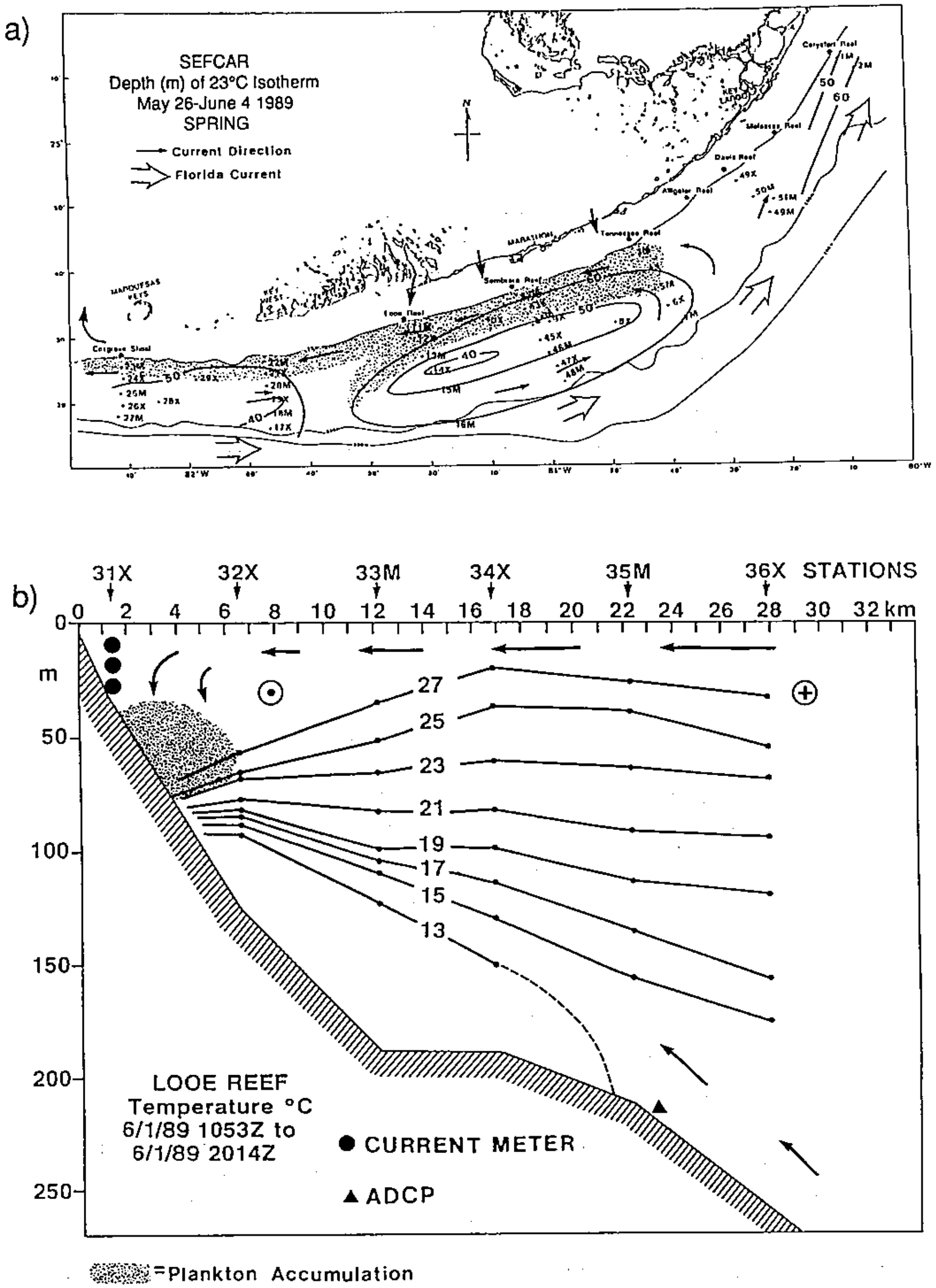

Fig. 12. (a) and (b). Schematic of larvae concentrations due to influence of Pourtales gyre circulation and prevailing easterly winds (towards west), superimposed on the spring survey temperature distribution.

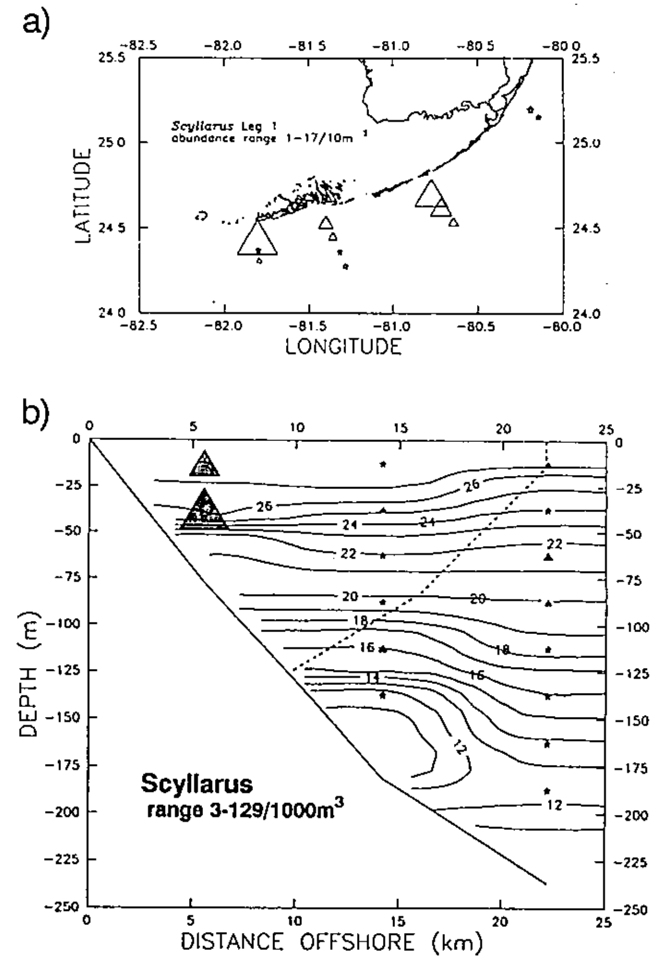

Fig. 13. (a) and (b). Concentrations of slipper lobster larvae during spring cruise in (a) upper layer and (b) in Looe Reef temperature section. Stages II–VII of nine possible stages were collected at the innermost station. Total larval duration for these species is approximately 90 days. The dotted line in (b) indicates the approximate position of the Florida Current front.

rotations around the gyre for local recruitment to occur, which is possible since the gyre duration is on the order of 1 month at times. An alternative local recruitment pathway could occur by westward transport in the wind driven coastal current followed by return flow in either the FC after entrainment into the cyclonic gyre observed off the Dry Tortugas (Vukovich, 1988) or through the Florida Bay and southeastward through the passes between the Keys. A net offshore flow of about 5 cm s^{-1} has recently been observed beneath the bridges of the southern Keys by Smith (personal communication) with year-long current meter records. The drift time for the Florida Bay recruitment path is very roughly estimated at 2 months, assuming a mean drift of 10 cm s^{-1} over approximately 500 km (Fig. 15). The drift time for larvae taking the Tortugas Gyre/FC pathway with return to the Looe reef area by the Pourtales Gyre/surface Ekman transport route would

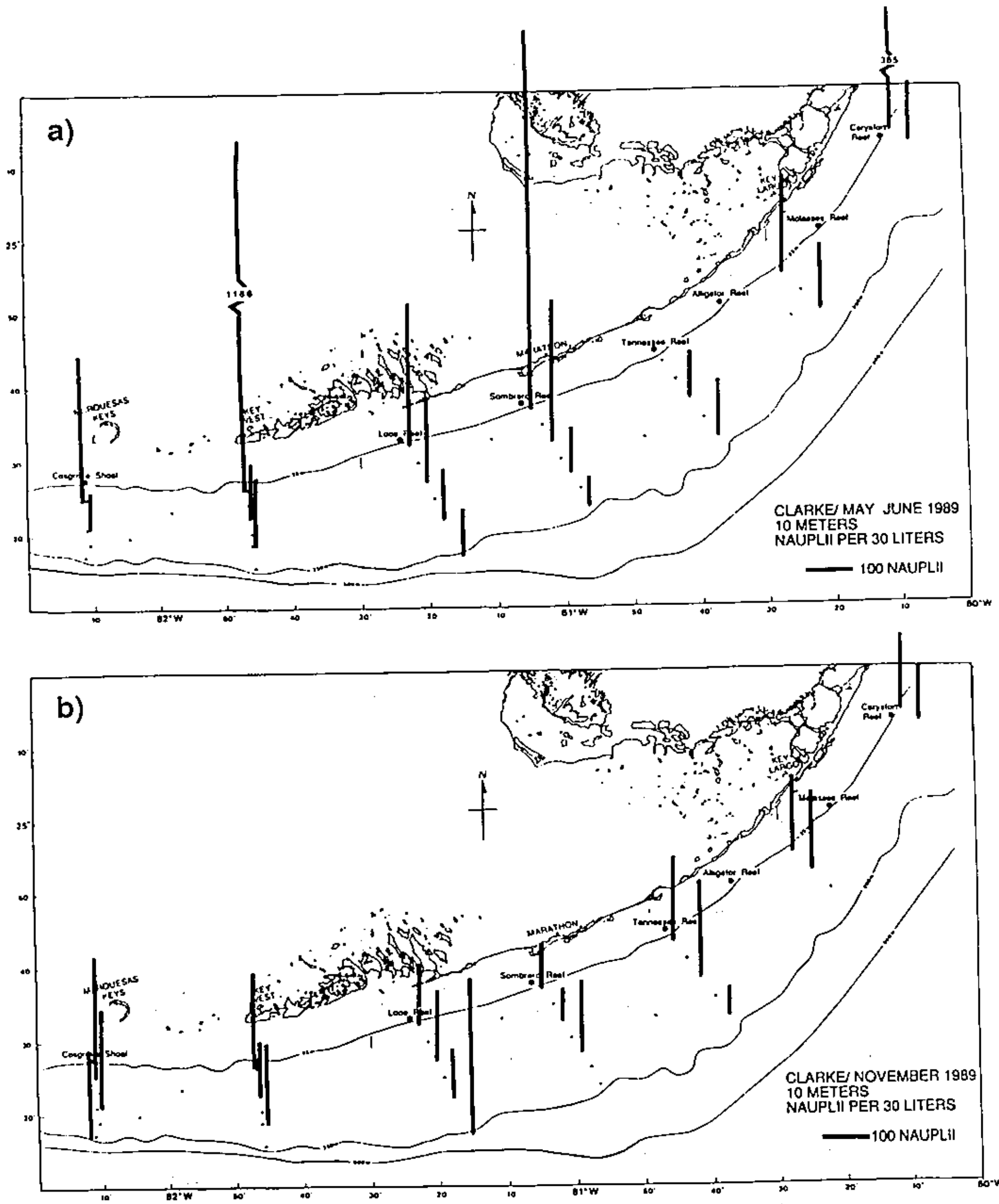

Fig. 14. (a) and (b). Concentration of microzooplankton (Nauplii) at 10 m during: (a) spring survey (gyre case), and (b) fall survey (no gyre case).

take about 30–50 days, using typical speeds for the gyres, FC and westward coastal current (Fig. 15). For local recruitment of spiny lobster larvae spawned in the offshore waters of the lower Keys to occur would require many circuits around the combined Pourtales Gyre/Tortuga Gyre pathway before the 6–12 months planktonic stage is completed. Since the duration of the Pourtales Gyre is about 1 month and it is unlikely that the Tortuga Gyre

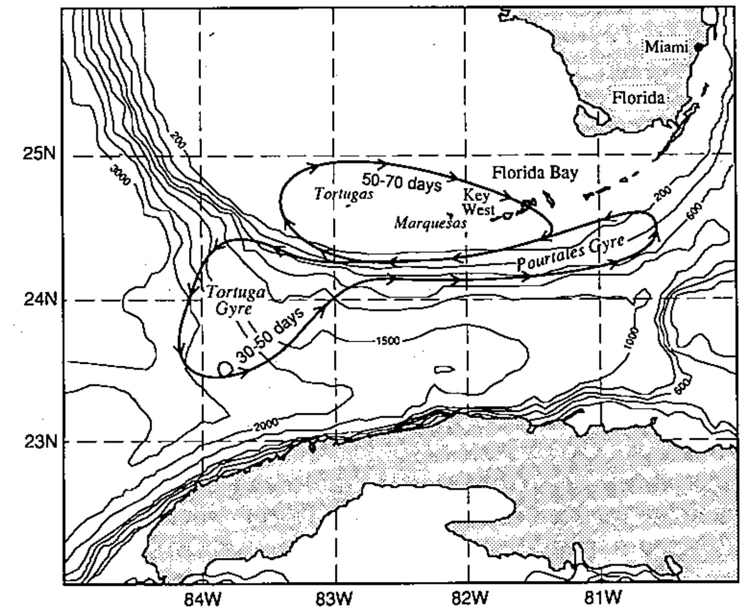

Fig. 15. Schematic of possible recruitment pathways for locally spawned fish and lobster larvae.

can last more than a few months at best, then it is highly doubtful that the FC and its gyres can serve as a local retention mechanism for Florida spiny lobster larvae. Therefore either Florida spiny lobster larvae are retained for long periods in the southwest Florida Shelf and Florida Bay followed by local recruitment or their source is found in remote upstream regions of the Caribbean and South America.

North of 25°N latitude the Straits of Florida are oriented north–south and the FC front is located close to the shelf edge. Eddy motions in this region have much smaller spatial scales than the Pourtales Gyre, and they are not trapped to a fixed location as at the turning points of the southern Straits, but rather propagate to the north with the mean flow (LEE and MAYER, 1977). Therefore the northern Florida Straits region will not have a retention mechanism for larvae spawned in offshore FC waters, which means that recruitment north of 25°N depends entirely on transport from upstream regions to the south.

6. CONCLUSIONS

A cold, cyclonic gyre is observed to form shoreward of the FC between Key Largo and Key West with a period of 1–2 months. Because the gyre appears to have a preference for formation over the Pourtales Terrace, we chose to name it the Pourtales Gyre. 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 s^{-1}. Upwelling velocities in the center of the gyre are estimated at 2 m day^{-1} and appear to cause a 50–75 m uplifting of cold, nutrient enriched 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 cyclonic flow curvature as the FC changes direction from eastward to northward flow due to the change in orientation of the Straits of Florida.

Local winds are predominantly from the southeast and appear to have little connection with formation of the Pourtales Gyre. In the lower Keys these local winds are primarily oriented in the alongshore direction and drive a westward coastal current near the offshore reefs. This response is typical of other shallow coastal seas with straight coastlines. However, in the middle and upper Keys where the coastline curves to the northeast and north, the prevailing winds are mostly onshore, which is not effective in generating alongshore flows.

The combination of the Pourtales Gyre and FC flow patterns under the influence of prevailing winds can produce a convergence of surface Ekman transports into the gyre and Terrace that can concentrate and retain plankton. Gyre induced upwelling provides a nutrient source to support an ecosystem response. The gyre and wind driven circulations may also aid the local recruitment of both fish and slipper lobster larvae spawned in the lower Keys, since the planktonic stages of these larvae have similar durations ($\sim$1 month), which is also the time scale of the gyre. Ichthyoplankton distributions are being determined, which will be used to evaluate this hypothesis.

In contrast, recruitment of locally spawned spiny lobster larvae in the Florida Keys is not likely unless they are retained in the southwest Florida Shelf or Florida Bay for long periods. This is because spiny lobster are believed to spawn in deep waters off the Keys (SIMS and INGLE, 1966) where larvae retention is not possible over their planktonic stage.

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