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MEAN DISTRIBUTION AND SEASONAL VARIABILITY OF COASTAL CURRENTS AND TEMPERATURE IN THE FLORIDA KEYS WITH IMPLICATIONS FOR LARVAL RECRUITMENT

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ABSTRACT

Long-term moored observations of current and temperature variability have been made along the offshore fringes of the Florida Keys reef tract from Carysfort Reef to the Dry Tortugas as part of multidisciplinary studies of larval recruitment processes (SEFCAR: South East Florida and Caribbean Recruitment) and studies of surface transport processes (SFOSRC: South Florida Oil Spill Research Center). These data are used to make robust estimates of magnitudes and patterns of mean flow and temperature fields in coastal waters of the outer shelf, and are compared to spatial patterns of the mean wind field measured at offshore Coastal Marine Automated Network (CMAN) weather stations and to the change in coastline orientation of the Florida Keys. Five years of moored current meter data from a station seaward of Looe Reef are analyzed using CMAN wind records and Acoustic Doppler Current Profile (ADCP) time series made offshore near the Florida Current front, revealing significant annual cycles in coastal current and temperature fields related to atmospheric and Florida Current forcing. These mean flow patterns and annual cycles are discussed in terms of their impact on larval recruitment pathways. The combined influences of downstream flow of the Florida Current, onshore Ekman transports in the upper layer, coastal countercurrents and cyclonic circulation in the Tortugas gyre tends to aid retention and ultimately recruitment of both locally- and foreign-spawned larvae into the Florida Keys. Seasonal cycles of currents and winds favors enhanced larval recruitment in the fall season of persistent northeast winds that can cause a coastal countercurrent over the entire length of the Keys from Key Largo to the Dry Tortugas, combined with seasonal maximum onshore surface Ekman transports and minimum downstream flow in the Florida Current.

Five years of moored observations of coastal currents and temperature from the outer shelf of the Florida Keys over the period April 1989 to April 1994 are combined with local CMAN wind records and current observations from offshore waters to describe mean distributions and seasonal cycles of the current and temperature fields. These data were collected as part of the NOAA supported study of South East Florida and Caribbean Recruitment (SEFCAR), and U. S. Coast Guard supported studies of surface transport processes by the South Florida Oil Spill Research Center (SFOSRC). Mean distributions and seasonal cycles of currents and temperature along the outer shelf of the Keys are shown to result from the combined influences of Florida Current forcing in the form of transient gyres, eddies and meanders, together with seasonal variations of Florida current transports, prevailing easterly winds and the cyclonic curvature of the coastline.

The physical setting of the Florida Keys coastal zone consists of a narrow (7–10 km) and shallow (<10 m) continental shelf curving cyclonically from a east-west orientation in the southern Keys to a near north-south orientation in the northern Keys (Fig. 1). Alongshore extent of the coastal zone is 300 km, stretching from the Dry Tortugas in the west to Key Largo in the north (which is also the extent of the Florida Keys National Marine Sanctuary). Topography of the region consists of a shallow nearshore zone with depths less than 3 m merging with a relatively deeper zone, Hawk Channel, with depths up to 10

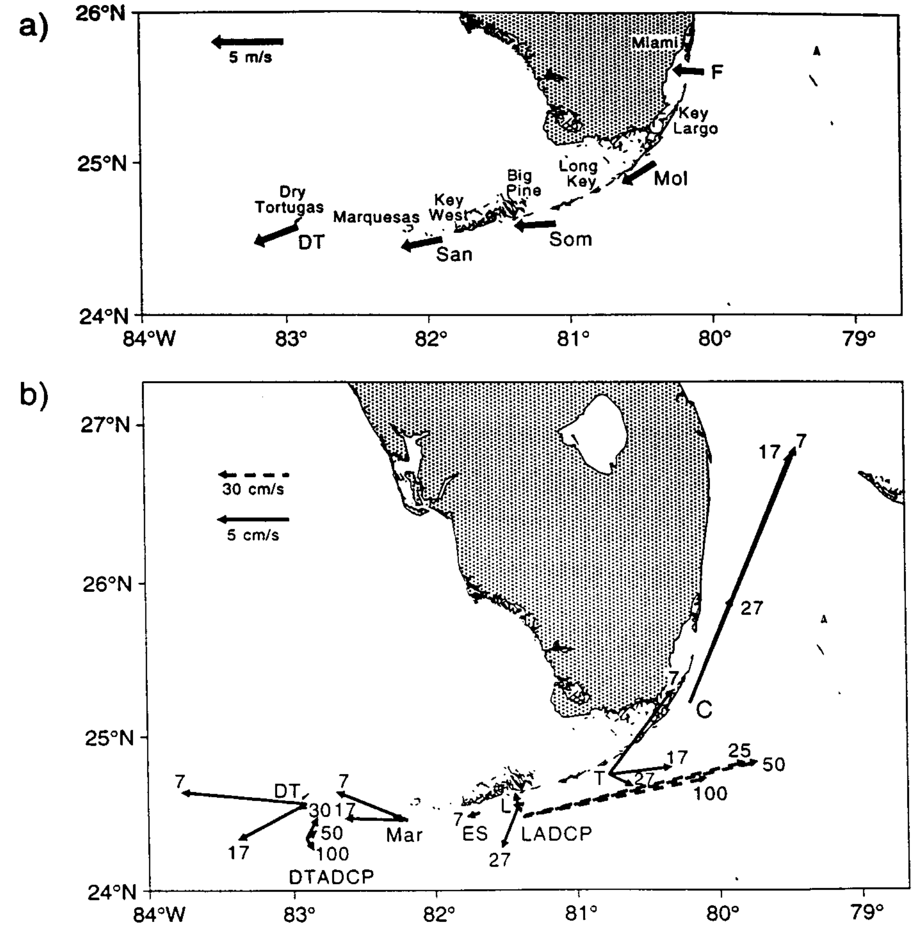

Fig. 1. Mean winds and currents for the period April 1989 to April 1994. Annual means are used except for those stations with fewer than 8 months of data where record lenght means are used (see Table 1). a) Mean wind vectors from CMAN stations at: Dry Tortugas (DT); Sands Key (San); Sombrero Reef (Som); Molasses Reef (Mol); and Fowey Rocks (F). b) Mean current vectors from moored current stations along the 30 m isobath at: Carysfort Reef (C); Tennessee Reef (T); Looe Reef (L); East Sambo (ES); Marquesas (Mar); and Dry Tortugas (DT) and from offshore ADCP stations at the Dry Tortugas (DTADCP) and Looe Reef (LADCP). Depths of current records are shown at the end of the arrows.

m. Seaward of Hawk Channel water depths again decrease and the bottom topography is complicated with a quiltwork of patch reefs and offshore massive coral structures of the fringing reefs. Water depths increase rapidly seaward of the reef tract to a shelf break near the 30 m isobath, then plunge several hundred meters in a steep continental slope that forms the shoreward side-wall of the Straits of Florida channel. Strong downstream flow (eastward and northward) of the Florida Current tends to follow the continental slope and forms the offshore, open boundary of the coastal zone. The shoreward boundary of the coastal zone is made up of the Florida Keys and tidal passages between the Keys, connecting the Atlantic coastal waters to the Gulf of Mexico and Florida Bay. The largest openings are in the western Keys between Marquesas and Dry Tortugas, and in the lower to middle Keys, between Big Pine and Long Keys (Fig. 1).

Previous studies of current variability in the Florida Keys coastal waters indicate that in the cross-shelf direction there are two distinct flow regimes, associated with responses to different forcing mechanisms. The first flow regime consists of the nearshore and Hawk Channel regions, where flow variability is controlled by tidal and local wind forcing (Lee, 1986; Pitts, 1994). Tidal currents are primarily in the alongshore direction (except for areas immediately adjacent to tidal passages between the Keys) and can account for 20 to 50% of the total current variance, but exhibit no significant tidal residual flow (Lee, 1986; Pitts, 1994). Low-frequency variability, primarily from local alongshore wind forcing, accounts for the remaining 50 to 80% of the total variance. The wind response appears typical of other shallow coastal zones with long, straight coastlines (Lee and Mayer, 1977; Csanady, 1982) and consists of significant alongshore flow events directly forced by local alongshore winds and are primarily responsible for seasonal mean flows (Lee, 1986; Pitts, 1994). However, the Florida Keys coastline curves from a east-west to north-south orientation and this can produce an interesting pattern of diverging alongshore flows forced by persistent easterly (westward) winds, with westward currents prevailing in the lower Keys and northward currents more common in the upper Keys (Pitts, 1994). Seasonal shifts in wind directions from southeast in summer to northeast in fall and east-northeast in winter and spring can cause seasonal shifts in mean alongshore current directions in the upper Keys that follow the seasonal wind shifts (Lee, 1986), whereas westward flow persists throughout the year in the lower Keys (Pitts, 1994).

The second flow regime is the outer shelf region where flow varibility is more strongly influenced by the Florida Current and wind forcing, and only to a lesser degree by tidal forcing. In the northern Keys and in the continuation of the coastal zone from Miami to Palm Beach, flow in the outer shelf is directly influenced by the passage of Florida Current meanders and eddys on weekly time scales. Low-frequency fluctuations account for approximately 75% of the total current variance and over 90% of the total temperature variance (Lee, 1975; Lee and Mayer, 1977; Lee and Mooers, 1977; Zantopp, Leaman and Lee, 1987; Lee, 1986; Lee et al., 1992). Local wind forcing accounts for only about 10% of the total alongshore current variability (Lee and Mayer, 1977). Close proximity to the Florida Current front at these locations also results in strong, persistent northward mean flows with significant vertical shear. In the southern Keys, the Florida Current influence occurs on a 30–60 d time scale due to the passage of cyclonic gyres that develop off the Dry Tortugas, in addition to the shorter weekly time scale of variability due to the occurrence of spin-off eddies frequently found in the northern Keys and off the coast of southeast Florida (Lee et al., 1992; Lee et al., 1994). Also, local alongshore wind forcing becomes more significant in the lower Keys due to the east-west orientation of the coastline, which aligns with the prevailing wind direction. The current response to the persistent westward alongshore winds results in downwelling along the coast, with onshore (offshore) flows in the upper (lower) Ekman layers and westward barotropic alongshore flow (Lee et al., 1992).

Observations

Subsurface, taut-wire current meter moorings have been maintained along the 30 m isobath between Dry Tortugas and Key Largo for durations of 1 yr or longer during the 5-yr period encompassing April 1989 to December 1994 (Fig. 1, Table 1). Currents and temperature were measured with General Oceanics current meters at depths of 7, 17 and 27 m. Mark I and II current meters

Table 1. Location of moored current stations and first order statistics for period April 1989–April 1994. Annual statistics were not computed for records with fewer than 8 calendar months of data. Units in cm sec^{-1} and ° C.

Instr. depth (m)	Record length (days)	Variable	Record length Mean	Record length ± SD	Annual Mean	Annual ± SE	%Variance 40hlp	%Variance (3–40)hlp
Amer. Shoal 24° 32.58′N, 81° 32.06′W Water Depth 13 m Rot: 73°								
6	226	u	0.7	1.2			23.4	76.6
6	226	v	–2.5	7.8			61.0	39.0
6	226	T	28.7	1.6			99.2	0.8
Carysfort 25° 12.25′N, 80° 12.25′W Water Depth 30 m Rot: 28°								
7	274	u	–2.0	3.9			36.8	63.2
7	274	v	19.1	18.4			49.9	50.1
7	274	T	26.5	2.1			99.6	0.4
17	527	u	–1.9	2.7	–1.9	0.40	26.8	73.2
17	527	v	19.7	16.7	19.8	2.40	45.5	54.5
17	527	T	26.7	2.3	26.6	0.09	99.4	0.6
27	231	u	-0.8	2.7			21.1	78.9
27	231	v	9.6	12.0			40.0	60.0
27	231	T	26.6	2.3	26.3	0.08	99.9	0.1
Tennessee 24° 44.63′N, 80° 46.79′W Water Depth 30 m Rot: 61°								
7	310	u	–3.0	8.0	–3.1	1.30	46.3	53.7
7	310	v	7.6	27.3	7.0	4.70	67.0	33.0
7	310	T	27.3	2.2	27.4	0.10	99.4	0.6
17	655	u	1.6	3.8	1.7	0.50	46.4	53.6
17	655	v	2.8	18.7	4.2	2.30	66.1	33.9
17	655	T	27.0	2.3	26.9	0.08	99.2	0.8
27	656	u	1.7	4.0	1.6	0.50	12.7	87.3
27	656	v	1.0	15.0	1.1	1.90	61.0	39.0
27	656	T	26.2	2.2	26.5	0.09	97.6	2.4
Looe Key 24° 32.53′N, 81° 24.11′W Water Depth 30 m Rot: 73°								
7	1,274	u	–0.7	3.3	–1.0	0.80	34.0	66.0
7	1,274	v	0.4	21.4	0.1	4.90	72.6	27.4
7	1,274	T	27.0	2.2	26.9	0.20	99.4	0.6
17	1,953	u	–0.2	2.6	–0.2	0.60	37.0	63.0
17	1,953	v	0.0	18.3	–0.3	3.60	73.2	26.8
17	1,953	T	26.8	2.4	26.7	0.40	95.2	4.8
27	1,365	u	2.3	3.6	2.5	0.80	42.5	57.5
27	1,365	v	–1.3	11.8	–2.1	2.60	66.3	33.7
27	1,365	T	26.8	2.4	26.4	0.20	98.4	1.6
East Sambo 24° 28.84′N, 81° 39.67′W Water Depth 30 m Rot: 73°								
7	227	u	0.6	2.3			28.1	71.9
7	227	v	–2.0	22.7			86.3	13.7
7	227	T	28.2	1.5			99.1	0.9
17	336	u	0.5	2.1	0.6	0.80	37.6	62.4
17	336	v	–1.9	17.6	–0.5	7.00	81.9	18.1
17	336	T	26.9	2.1	26.9	0.20	99.3	0.7
27	242	u	–0.3	2.0			28.8	71.2
27	242	v	2.8	7.9			66.7	33.3
27	242	T	28.0	2.0			95.5	4.5

Table 1. Continued

Instr. depth (m)	Record length (days)	Variable	Record length Mean	Record length ± SD	Annual Mean	Annual ± SE	%Variance 40hlp	%Variance (3–40)hlp
Marquesas 24° 27.11′N, 82° 11.41′W Water Depth 30 m Rot: 90°								
7	842	u	–2.2	3.0	–2.0	0.80	15.1	84.9
7	842	v	–4.0	12.8	–5.0	3.40	67.7	32.3
7	842	T	27.0	2.3	26.7	0.20	99.4	0.6
17	600	u	–0.4	3.3	–0.1	0.80	22.3	77.7
17	600	v	–2.6	9.4	–5.0	2.70	62.0	38.0
17	600	T	27.4	1.8	27.1	0.20	97.3	2.7
27	377	u	–0.7	5.1	–0.9	1.50	44.3	55.7
27	377	v	–1.2	6.2	–1.2	2.40	46.5	53.5
27	377	T	25.7	2.3	25.5	0.30	95.7	4.3
Dry Tortugas 24° 33.60′N, 82° 54.03′W Water Depth 30 m Rot: 104°								
7	296	u	1.3	6.8			17.4	82.60
7	296	v	–8.4	8.6			30.8	69.20
7	296	T	28.3	1.9			99.7	0.30
17	451	u	3.7	5.6			18.2	81.80
17	451	v	–4.1	5.1			22.8	77.20
17	451	T	25.8	2.6			99.6	0.40
27	122	u	0.6	1.4			11.7	88.30
27	122	v	–0.5	1.1			13.4	86.60
Looe Key ADCP 24° 28.39′N, 81° 21.61′W Water Depth 150 m Rot: 73°								
25	938	u	1.2	10.1	2.3	2.40		
25	938	v	46.6	57.4	47.1	13.90		
50	940	u	1.6	10.4	3.0	2.50		
50	940	v	49.4	56.9	49.8	13.60		
100	940	u	2.5	7.1	3.2	1.60		
100	940	v	39.8	35.3	38.8	8.40		
Dry Tortugas ADCP 24° 19.92′N, 82° 54.18′W Water Depth 200 m Rot: 104°								
30	373	u	–1.8	9.3	–1.7	3.20		
30	373	v	1.1	41.4	0.5	14.00		
50	373	u	–0.9	7.8	–0.8	2.80		
50	373	v	1.1	37.6	0.6	13.10		
100	373	u	0.6	4.9	0.7	1.80		
100	373	v	1.1	31.5	0.7	11.90		

were used with burst sampling over a 32-s period to reduce surface wave noise. The Looe Reef site has been maintained continuously and there are now over 7 yrs of data at this site. The upper and middle Keys sites at Carysfort and Tennessee Reefs were in operation from April 1989 to April 1991. The western Keys site off Marquesas was active for more than 3.5 yrs, from April 1991 to November 1994, and the Dry Tortugas site was maintained for 1 yr, from April 1991 to May 1992. In addition bottom-moored ADCP's were deployed offshore of the Dry Tortugas at the 200 m isobath from April 1991 to May 1992, and at the 150 m isobath off Looe Reef for the periods August to November 1989; April 1990 to April 1991; and July 1993 to November 1994, to measure variations of the Florida Current. Wind records were obtained for the same 5-yr period from the offshore CMAN stations positioned on lighthouses at Fowey Rocks, Molasses Reef, Sombrero Reef, Sands

Table 2. CMAN Station locations and wind statistics for 5-yr period, April 1989 to April 1994. Wind units are in m s^{-1}. Wind rotations along isobaths are shown.

Station	Record length (days)	Variable	Record mean	Record ± SD	Annual mean	Annual ± SE
Fowey Rocks						
25° 35.4′N	948	u	–2.4	3.6	–2.2	0.5
80° 06.0′W		v	0.4	3.2	0.3	0.3
Rotation: 0°						
Molasses Reef						
25° 00.6′N	1,826	u	–0.8	3.4	–0.8	0.2
80° 22.8′W		v	–2.7	3.7	–2.7	0.3
Rotation: 40°						
Sombrero						
24° 37.6′N	1,826	u	–0.7	3.4	–0.7	0.2
81° 06.6′W		v	–2.7	3.4	-2.8	0.3
Rotation: 73°						
Sand Key						
24° 27.4′N	1,368	u	–0.3	3.7	0.1	0.3
81° 52.7′W		v	–3.0	3.4	–2.9	0.3
Rotation: 80°						
Dry Tortugas						
24° 38.3′N	699	u	1.9	3.2	2.0	0.2
82° 51.7′W		v	–2.7	3.5	–2.6	0.3
Rotation: 104°						

Key and Dry Tortugas (Fig. 1). The wind time series are of different record lengths due to sensor malfunctions (Table 2) and this can cause discrepancies in the annual mean wind patterns. The most complete records were from the Sombrero and Molasses stations. All time series are filtered with a 40-h low pass (hlp) Lancoz filter to remove tidal variations then subsampled at 6-h intervals. Current and wind vectors are rotated into an along- and across-isobath coordinate system, where v is positive in the downstream direction (eastward in the lower Keys and northeastward in the upper Keys) and u is positive in the offshore direction. Wind records were extrapolated to a standard 10 m height using:

$$U_{10} = U_Z[\ 10/z]^{0.1}$$

from Kourafalou et al. (1996), where Z is the height above the sea surface and U is the wind speed, and then converted to wind stress, τ using:

$$\tau = \rho\ C_D\ (U_{10})^2$$

where ρ is air density and C_D is the drag coefficient with an assumed value of 1.5×10^{-3}.

Results

Mean Properties.—Averages over the total record lengths, as well as annual averages of current, temperature and wind time series, are given in Tables 1 and 2. Annual averages are computed as the averages of monthly means. Annual averages are more representative of the long term mean conditions in the Keys coastal waters, where significant annual cycles could cause discrepancies in short record length means that end at different phases of the annual cycle. Also reported are the instrument locations, rotation angles used to convert velocity vectors into the isobath coordinate system, the total record lengths, standard deviations (SD), standard error of the means (SE), and the percent of the total variance due to low-frequency (40 hlp filtered) and high frequencey (3–40 h bandpass) variations. The standard error is computed from: SE = SD/(df)$^{1/2}$, where df is the degrees of freedom, given by the record length (days) divided by the time scale (Press et al., 1992). The standard error of the mean currents and temperatures were computed using a 10-d time scale for the upper Keys sites (typical time scale of Florida Current meanders and frontal eddies in the upper Keys) and a 60-d time scale for the lower Keys sites (typical time scale of Florida Current meanders and gyres in the lower and western Keys, from Lee et al., 1994). A 10-d time scale typical of the most energetic period for wind forcing was used to compute SE of the wind records. Annual statistics are not shown when there were fewer than eight calendar months of data.

Generally the record length averages agree quite closely with the annual means, with differences usually less than 1 cm s^{-1} for the currents, 0.3°C for temperature and 0.2 m s^{-1} for winds, and no significant differences in sign. This indicates that the record lengths are sufficiently long to produce reasonably stable mean conditions. Robust estimates of mean temperature were made for all sites with standard errors less than 0.7°C. Mean alongshore flows were well resolved at those locations with strong mean currents, e.g., the upper Keys and the offshore ADCP site off Looe Key, where standard errors were typically less than half of the means. Whereas, at coastal sites with weak mean flows the standard errors ranged from 2–5 cm s^{-1} and could be several times the mean. The most uncertain mean flow occurred at the offshore ADCP site at the Dry Tortugas, where yearlong mean flows were about 1.0 cm s^{-1} and standard errors were 12–14 cm s^{-1}. Standard deviations of the alongshore currents at this site were about 40 cm s^{-1}, and reflect the location of the site, which at times is characterized by strong westward flows during Tortugas gyre events (which can last 2–3 mo), and at other times by strong eastward flow events, which can last for about 1 mo when the Florida Current front meanders onshore (Lee et al., 1994). Standard errors of cross-shelf currents are typically about the same magnitude as the means, except again for the Dry Tortugas ADCP site where the standard errors are about twice the mean. Annual mean winds are well resolved over the 5-yr period and are nearly equal in magnitude, even though record lengths varied at the different sites from 2–5 yrs (Table 2). Mean winds were toward the west at about 2–3 m s^{-1} with standard errors generally less than 0.3 m s^{-1}.

COMPARISON OF LOW- AND HIGH-FREQUENCY VARIANCE.—The percent of total variance of coastal current components and temperature due to low-frequency (subtidal) and high-frequency (total variance minus 40 hlp time series variance) fluctuations are shown in Table 1 for all stations at the 30 m isobath. Subtidal motions account for about 70% of the total alongshore current variance at upper and mid-water positions at all coastal sites except for the Dry Tortugas where about 70% of the variance is explained by tidal and inertial motions. In the lower layer approximately 50 to 60% of alongshore current variance is accounted for by subtidal motions, again except for the Dry Tortugas where only 10% is due to low-frequency variations. In the region from Key Largo to Key West approximately 50 to 70% of the total variance of cross-shelf currents is explained by tidal and inertial motions. In contrast, at the Marquesas and Dry Tortugas sites, which are more openly connected to the Gulf of Mexico, tidal and inertial motions account for about 85% of the total cross-shelf current variance. Temperature variability is dominated by low-frequency fluctuations at all sites, accounting for greater than 95% of the total variance.

In the western Keys (openly connected to the Gulf of Mexico), coastal current variability results primarily from tidal and inertial motions due to strong tidal interaction between the Gulf and Atlantic at diurnal and semi-diurnal periods (Zetler and Hansen, 1970). The semi-diurnal variability results from a semi-diurnal tidal wave propagating from the Atlantic through the Straits of Florida. The diurnal variability is due to the diurnal tidal wave of the Gulf of Mexico that oscillates near the natural period of the basin. The inertial period at this latitude is also close to the diurnal period, which can provide further high-frequency current variance.

Alongshore coastal currents at the Dry Tortugas site show a significant westward mean flow of about −8.0 cm s^{-1} in the upper layer with little subtidal variability (Table 1, standard deviations of low-frequency alongshore current records are about equal to the mean). Whereas, on the slope offshore of this site, the ADCP records show weak eastward mean flows of about 1.0 cm s^{-1} and strong subtidal variability with standard deviations of about 40 cm s^{-1}. In the region between Key West and Key Largo the exchange between the Gulf of Mexico and the Straits of Florida occurs through relatively narrow channels compared to the large open areas to the west of Key West. Variability of alongshore coastal currents in this region is dominated by subtidal motions from both wind and Florida Current forcing in the form of downstream passage of meanders, frontal eddies and gyres (Lee et al., 1992, 1994). Both wind and frontal eddy events occur on time scales of about 1 wk, whereas gyre events occur on 1–2 mo time scales.

SPATIAL PATTERNS OF MEAN CURRENT, TEMPERATURE AND WIND FIELDS.—Annual mean current and wind vectors from each site are shown in Figure 1 for the 5-yr period 1989–1994. Mean wind vectors are toward the west at all sites and are of similar magnitude. The observed small deviations in mean wind directions are more likely due to differences in record lengths (Table 2), rather than statistically meaningful direction shifts. Subtidal wind records normally show a high degree of spatial coherence over south Florida and the Keys due to both the zonal orientation of the CMAN stations in a westward wind regime, and to the large spatial coherence scales of synoptic wind forcing events. The cyclonic curvature of the Keys coastal boundary results in mean wind vectors being oriented mostly cross-shore in the upper Keys, and alongshore from the middle and lower Keys out to the Dry Tortugas. Mean coastal currents show the influence of both the persistent westward winds, the Florida Current and coastal gyres. In the upper Keys strong mean downstream flows occurred with considerable vertical shear, indicating direct influence from the nearby Florida Current front. At the Tennessee Reef middle Keys mooring site mean currents show considerable decrease in amplitude and change in direction with depth, i.e., upper currents strong in the downstream and onshore directions and near-bottom currents predominantly offshore. In the lower and western Keys the mean flow was westward and steadily increased from Looe Reef to the Dry Tortugas. A westward coastal counter-current is to be expected from the westward wind forcing. However, the westward intensification of the counter-current appears to be related to the prolonged duration of the Tortugas gyre off the Dry Tortugas. Lee et al. (1994) show that this cyclonic gyre is a persistent feature off the Tortugas causing westward flow on the northern side of the gyre that can last up to 3 mo. The presence of the gyre causes the Florida Current front to be displaced

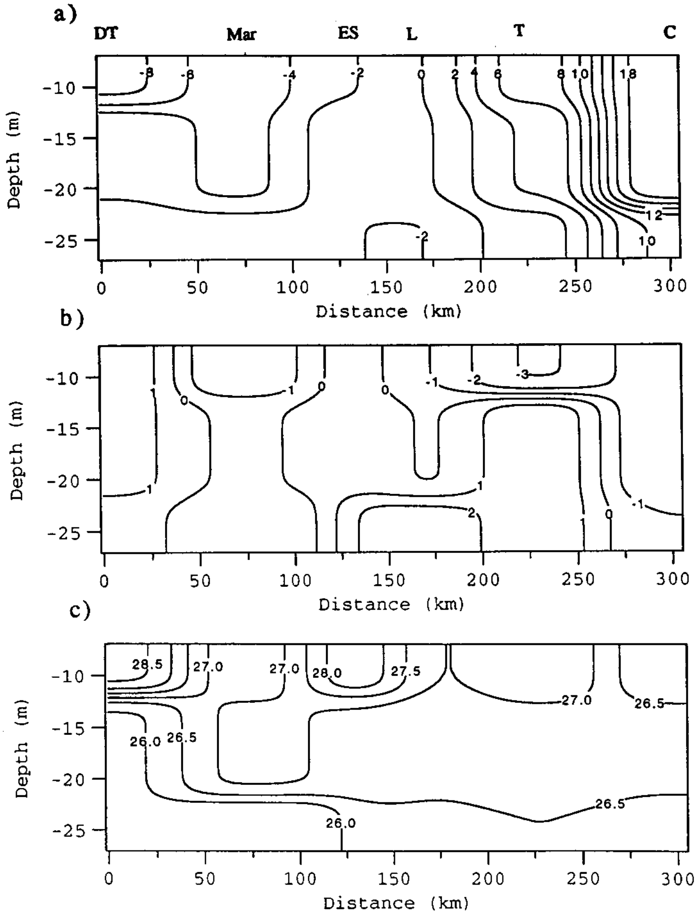

Fig. 2. Alongshore distribution of annual mean: a) alongshore currents (cm/s); b) cross-shore currents (cm/s); c) temperature (C) at the 30m isobath. Position of mooring sites are given at the top using the same identifications as in Fig. 1.

further offshore on the mean than at any other location in the Straits. The combined effect of the gyre circulation and the offshore displacement of the Florida Current results in the weak mean eastward flows observed at the ADCP site off the Dry Tortugas (Fig. 1). The more shoreward mean position of the Florida Current front off Looe Reef results in the strong downstream mean flows observed at the nearby ADCP site on the Pourtales Terrace.

The alongshore distributions of alongshore and cross-shore mean flows and temperature at the 30 m isobath are shown in Figure 2. There is a mean alongshore flow divergence, with strong downstream (northward) flow in the upper Keys and upstream (westward) flow in the lower Keys out to the Dry Tortugas. Compensation for this flow divergence may occur as inflow from the Florida Current, as suggested by the strong onshore mean flow at Tennessee Reef (Fig. 2B). Additional compensation may occur as inflow from the Gulf of Mexico and Florida Bay through the Keys passages, as shown by Smith (1994) and Lee et al. (1996). In the upper Keys at Carysfort Reef a vertically sheared, strong northward mean flow occurred with an onshore component over the entire water column. Downstream mean flow was nearly 20 cm s^{-1} in the upper 20 m and decreased sharply to about 10 cm s^{-1} near the bottom. Onshore mean flows were about −1 to −2 cm s^{-1} (negative is onshore) at all depths. A strong northward mean baroclinic flow at this location indicates a close proximity to the cyclonically- and vertically-sheared Florida Current front, where downstream flows increase rapidly with distance offshore and above the bottom. The observed onshore mean flows over the total water column suggest a shoreward convergence of the Florida Current front, which occurs following the cyclonic northward turn of the current in the middle Keys. Onshore mean flows were maximum in the upper layer at the Tennessee Reef site, which could be explained by the shoreward movement of the Florida Current in this area in combination with onshore Ekman transports and partial compensation for the mean alongshore flow divergence.

The trend of increasing upstream mean flows from the lower Keys to the Dry Tortugas occurs due to the combined effects of alongshore wind forcing and the increased persistence of coastal gyres offshore of the Dry Tortugas. The east-west orientation of the coastline and bottom topography in the lower Keys is more aligned with the prevailing westward winds resulting in significant alongshore wind forcing compared to the upper Keys where cross-shelf winds prevail (Fig. 1). Westward wind forcing will result in nearly barotropic westward alongshore flow, typical of the Looe Reef area, combined with onshore flow in the upper Ekman layer and offshore flow in the lower layer, which occurred on the average from Looe Reef to Marquesas (Figs. 2A,B). The longer durations of cyclonic coastal gyres off the Dry Tortugas (60–100 d) enhances the magnitude of the upstream mean flow, compared to the Looe Reef area where gyre durations are only about one month or less (Lee et al., 1994). The gyre circulation off the Dry Tortugas also appears to result in a mean offshore flow in the upper layer at this site, overcoming the onshore Ekman transports typical of this downwelling coastal regime. Without the gyre influence the mean alongshore and cross-shore flows would be nearly uniform along the east-west oriented coastal zone of the lower Keys. The persistence of cyclonic gyres off the Dry Tortugas and their accompanying upwelling also appears to have a significant influence on the mean temperature field at the 30 m isobath, resulting in increased stratification and colder lower layer mean temperatures in the west (Fig. 2C). There is also a trend of increasing upper layer temperatures from the upper Keys to western lower Keys.

ANNUAL CYCLES.—Five years of current meter data from the Looe Reef site and CMAN wind records for the period April 1989 to April 1994 were used to compute monthly averaged time series to investigate seasonal variability. Ensembles of monthly average alongshore and cross-shore wind stress components are shown in Figure 3 for Fowey, Molasses, Sombrero and Sand Key stations. Records from the Fowey Rock Light station are characteristic of an upper Keys site with no isobath rotation, and the Sombrero and Sand Key stations are representative of lower Keys sites with isobath rotations of 73° and 90°, respectively. Standard errors of the monthly means are small in comparison to the scale of the seasonal cycles, giving robust estimates of seasonal variability with the available data. The monthly average alongshore wind stress was consistently negative (toward the west or southwest) at the middle and lower Keys sites, and shows similar annual cycles of maximum westward/southwestward wind during the fall to early winter period of October to January and minimum alongshore wind during the summer (June to August). There is also a weaker, secondary maximum in the spring (April and May). The northern Keys site (Fowey) showed a similar pattern with maximum southward wind

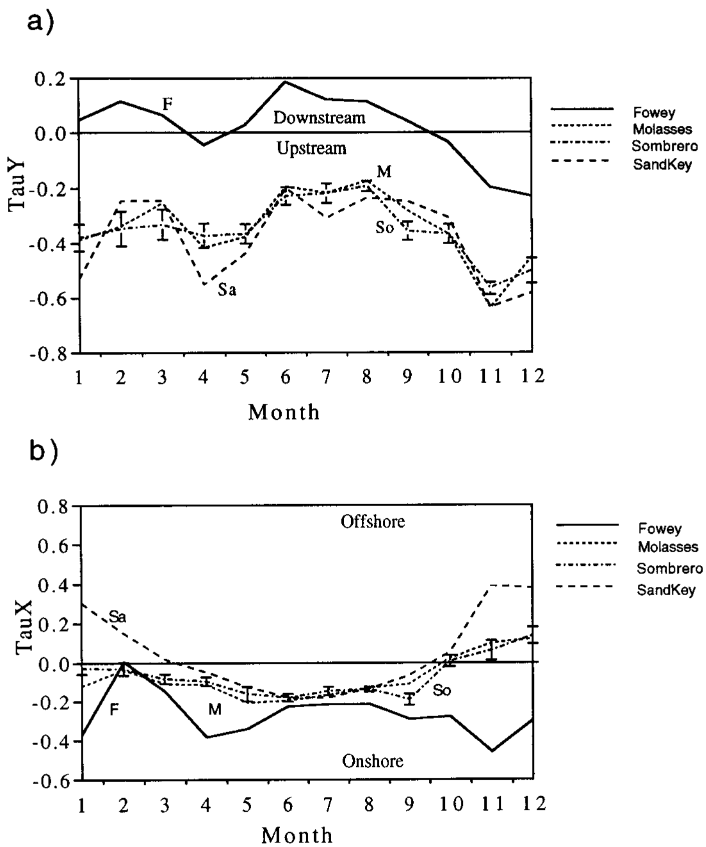

Fig. 3. a) Alongshore and b) cross-shore monthly mean wind stress components from CMAN wind stations, site identifications are the same as in Fig. 1. Error bars indicate standard error of the means for the Sombrero site. Record lengths are given in Table 2.

stress in the fall and maximum northward wind in the summer when southeasterly winds prevail. Alongshore wind stress was consistently stronger in the lower Keys than in the upper Keys due to the curvature of the coastal zone. However, this difference becomes smaller in the fall (October to November) when persistent winds from the northeast occur. The effect of isobath curvature is clearly shown by comparison of the seasonal patterns of cross-shore wind stress (Fig. 3B). At the upper Keys site cross-shore wind stress was onshore for all months with little seasonal variation and was consistently stronger than at the lower Keys site. Whereas, at the lower Keys sites cross-shore winds show a significant seasonal pattern of onshore winds prevailing from April to September, with a maximum in the summer, and then shifting to offshore in the fall when winds from the northeast prevail.

Monthly average alongshore and cross-shore currents and temperature from the Looe Reef site are shown in Figure 4. Standard errors of the monthly means are only shown for the instrument at 17 m to make the figure less cluttered. However the 7 and 27 m means have similar error bars and indicate that the seasonal cycles shown are statistically well resolved. Monthly mean alongshore currents have a significant seasonal cycle with maximum eastward flow occurring in late winter/early spring (February to March) and again

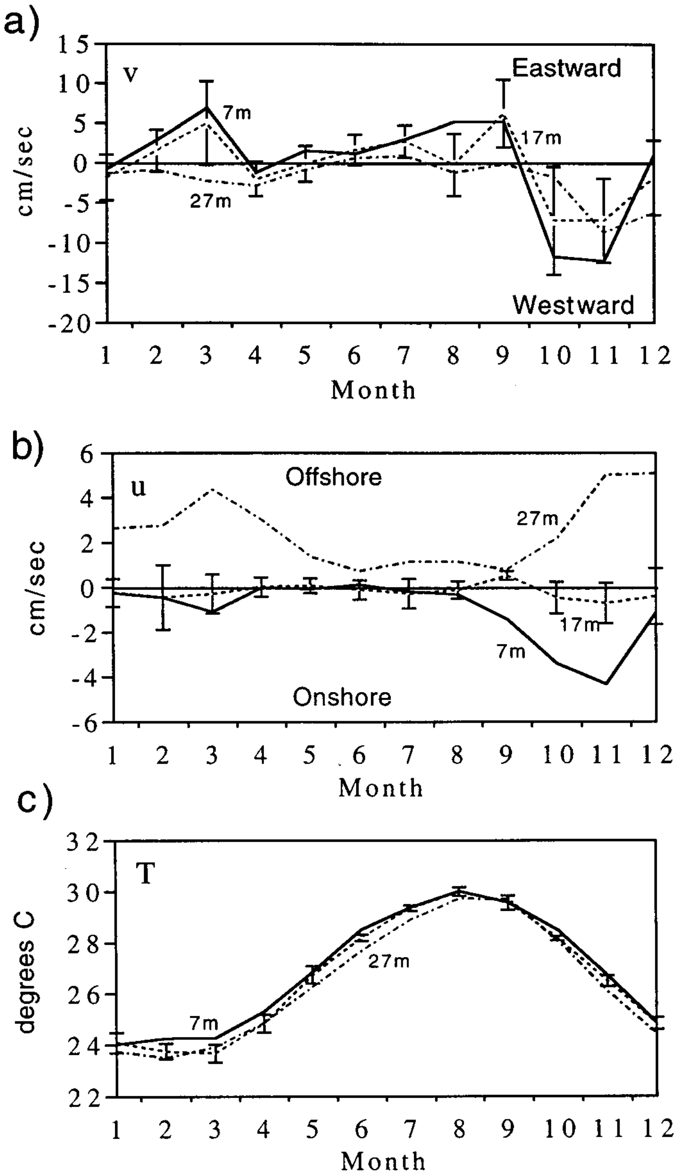

Fig. 4. Monthy mean a) alongshore currents, b) cross-shore currents and c) temperature from the Looe Reef coastal mooring site from April 89 to April 94. Error bars display the standard error of the means at the 17 m level. Record lengths are given in Table 1.

in late summer (July to September). Maximum westward flow occurred in the fall (October to November). This pattern was similar at all depth levels, except the amplitude was weaker in the lower layer and the spring eastward maximum was not observed there. The annual cycle of alongshore currents resembles the annual cycle of alongshore winds (Fig. 3), especially in the lower layer where westward flow persists. The fall maximum of westward flow occurred during the time of maximum westward wind stress. The summer maximum of eastward flow occurred during the period of minimum westward wind stress, which suggests that the seasonal alongshore currents are also influenced by the seasonal cycle of the Florida Current with maximum downstream transport in the summer and minimum in the fall (Niiler and Richardson, 1973; Lee and Williams, 1988). Also the second maximum in eastward flow during late winter/early spring is at odds with the seasonal alongshore winds and suggests a Florida Current source.

The seasonal cycle of cross-shore currents appears to be the result of Ekman response to alongshore wind forcing (Fig. 4B). Cross-shore flows in the upper and lower layers are out of phase and closely follow the seasonal cycle of alongshore winds. Both maximum onshore (offshore) flows in the upper (lower) layers occurred at the time of maximum westward winds in the fall and spring (Fig. 3A). Evidence that the cross-shore flows were directly wind forced is also shown by the weak cross-shore flows in the summer when alongshore winds were weak and alongshore currents were strong eastward. At mid-depth monthly averaged cross-shore flow is near zero.

The annual cycle of monthly averaged water temperatures at the Looe Reef site has a maximum in summer of about 30°C and minimum in winter near 24°C that clearly follows the annual cycle of air temperature in the Keys (Fig. 4C). The seasonal change in temperature stratification also appears to be atmospherically forced with minimum temperature difference between the upper and lower layers occurring in the fall and early winter during maximum wind mixing and maximum temperature difference occurring in late winter/spring and summer during weaker wind mixing periods.

Discussion

The spatial pattern of mean coastal flows seaward of the reef tract in the Florida Keys, as well as their seasonal cycles appear to result from the combined influence of wind and Florida Current forcing. Winds in the Keys are persistent toward the west throughout the year, except for short intervals, usually less than 1–2 d, when the wind veers out of the west and northwest during the passage of atmospheric lows and winter cold fronts. The cyclonic curvature of the Keys coastline and shelf causes westward alongshore wind forcing to prevail in the lower and western Keys from about Big Pine Key to the Dry Tortugas that drives a mean westward coastal current (Figs. 1,2). The westward acceleration of this countercurrent results from a persistent cyclonic gyre (Tortugas gyre) that forms over the slope south of the Dry Tortugas as the Loop Current in the eastern Gulf of Mexico makes an abrupt cyclonic turn into the Straits of Florida, sometimes overshooting the entrance by half the channel width (Chew, 1974; Lee et al., 1994). These gyres can persist for several months off the Tortugas before they begin to slowly move into the Straits and decrease in size. The gyres are observed in currents off Looe Reef for up to 1-mo durations, where they are about half their original size as when they are off the Tortugas (Lee et al., 1992; 1994). They are rarely observed in the middle or upper Keys. Mean cross-shelf flows in the lower Keys appear to be an Ekman response to the alongshore wind forcing, onshore in the upper layer and offshore in the lower layer, typical of the downwelling coast. However, this cross-shelf flow pattern also appears to be influenced by the gyre circulation in the western Keys and becomes offshore at the Tortugas (Table 1, Fig. 2B).

In the upper Keys the prevailing westward winds are primarily in a cross-shore direction, and significant alongshore currents do not develop due to the lack of an alongshore coastal boundary. Currents seaward of the reefs in the upper Keys result primarily from the direct influence of the nearby Florida Current that converges toward shore in this region after making the northward turn of the Straits off the middle Keys (Lee et al., 1992). Alongshore mean flows off Carysfort Reef are strong downstream with considerable vertical shear and cross-shelf mean flows are onshore over the total water column (Table 1, Figs. 1,2A,B).

The middle Keys outer shelf waters are a transition zone between the downwelling coast of the lower Keys and the strong Florida Current influence of the upper Keys. Considerable divergence occurs in mean alongshore flows between the Looe Reef and Tennessee Reef sites (Figs. 1,2A). Apparently this divergence is compensated by the shoreward convergence of the Florida Current causing the strongest onshore mean flow (-3.0 cm s^{-1} in the upper layer at Tennessee) observed anywhere in the Keys (Table 1, Fig. 2B), as well as strong downstream mean flow and offshore flow near the bottom. Additional compensation could be provided by a net southeastward flow from the Gulf of Mexico and Florida Bay observed by Smith (1994).

Seasonal wind patterns in the Keys result in weak southeasterly winds in summer, stronger northeasterlies in the fall and moderate to strong east to northeasterlies in the winter and spring (Table 2; Fig. 3). Because of the curving coastline, the fall season with increased winds towards the west and southwest, becomes the dominant alongshore wind forcing season for the entire Keys from the Dry Tortugas to Key Largo (Fig. 3). Seasonal variations of currents off Looe Reef determined for the same 5-yr period as the seasonal winds are significantly correlated with alongshore winds (Fig. 5A). Maximum westward monthly mean alongshore flows, together with the strongest downwelling-type Ekman cross-shelf mean flows, occurred simultaneously with the fall annual westward peak in alongshore wind forcing (Fig. 5A,B). A similar seasonal pattern is found in the monthly averaged and seasonal averaged alongshore currents for the entire length of the Florida Keys (Fig. 6). Seasonal averages of the alongshore currents provide some smoothing to small irregularities in the monthly means caused by differences in deployment periods and record lengths and clearly show the seasonal pattern of maximum downstream flow in the spring and summer and maximum upstream flow in the fall at all sites that matches the seasonal pattern of alongshore wind stress. This pattern is displaced in a downstream direction at Carysfort and Tennessee sites due to the strong influence of the Florida Current in the upper Keys. The Looe Reef site represents a transition region between the Florida Current dominated upper Keys and wind and gyre dominated western Keys and as a result the seasonal current pattern is downstream in spring and summer and upstream in fall and winter. The pattern shifts to a upstream orientation at the Marquesas western Key site where winds are primarily toward the west and gyre influence becomes stronger.

The Florida Current annual cycle of volume transport also appears to influence the seasonal cycle of alongshore coastal currents in the Keys outer reef tract, especially in the middle to upper Keys. The Florida Current volume transport has been well observed over multiple years at 26°N and 27°N (Niiler and Richardson, 1973; Molinari et al., 1985; Lee et al., 1985; Leaman et al., 1987; Larsen, 1992). The annual cycle of monthly mean volume transport anomalies (demeaned) as determined from moored current meter arrays (Schott et al., 1988) is shown in Figure 5C, together with the annual cycle of alongshore currents off Looe Key. The annual transport cycle has been shown to result from a combi-

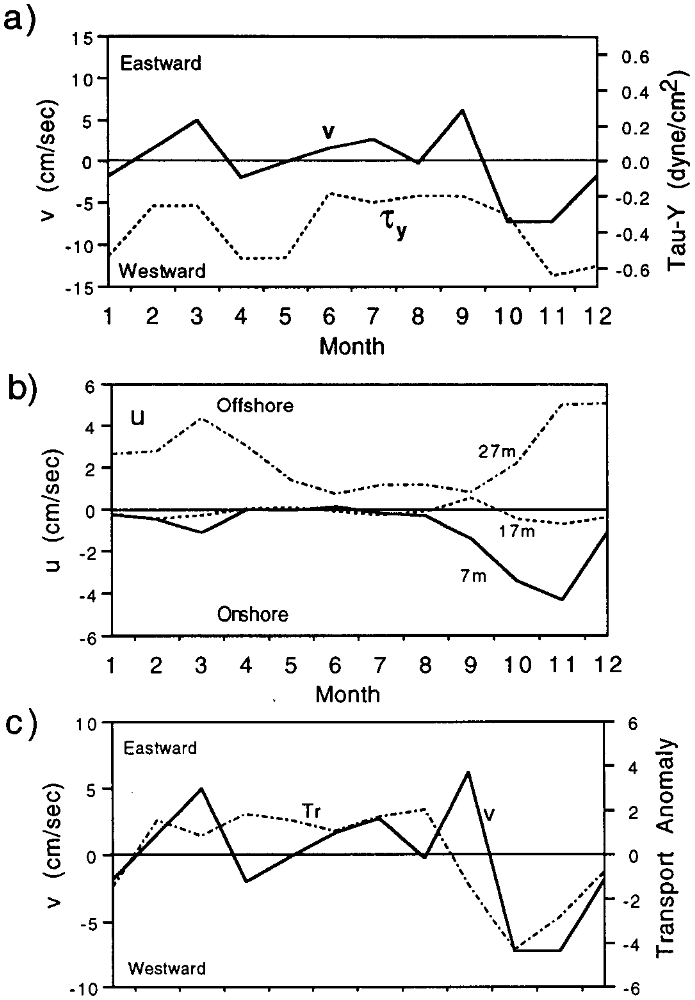

Fig. 5. Monthly mean a) alongshore current at 17m from Looe and alongshore wind stress at Sand Key; b) cross-shore currents at Looe; c) alongshore current at 17m from Looe with the Florida Current demeaned annual volume transport cycle (in Sverdrups=$10^6 m^3/s$) from moored records at 27° N for the period April 84 to April 86.

nation of local and remote wind forcing (Anderson and Corry, 1985; Lee and Williams, 1988; Schott et al., 1988), which explains why the transport is minimum in the fall when along-channel winds are maximum in the upstream direction over the entire length of the Straits of Florida. Florida Current volume transports show a broad maximum during the spring and summer that appears to match the maximum seasonal averaged alongshore flows observed in the outer shelf over the entire length of the Keys during this period of weaker mean alongshore winds (Fig. 6). The Florida Current seasonal transport pattern is clearly shown in the seasonal cycle of alongshore currents off Tennessee and Carysfort Reefs with the Florida Current influence becoming stronger at the more northerly sites due to the convergence of the Stream toward shore in the upper Keys.

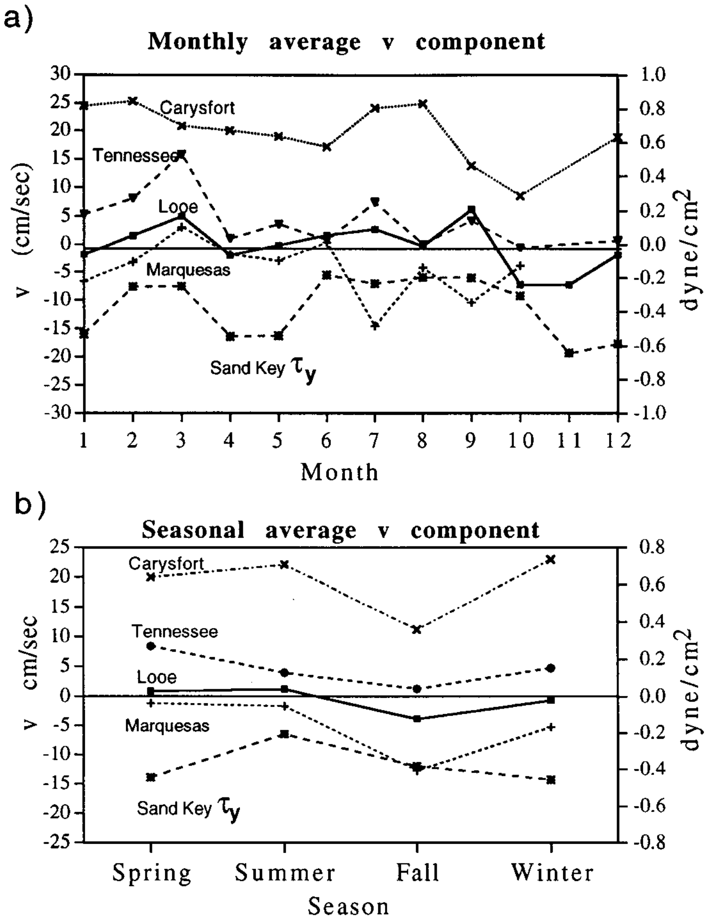

Fig. 6. Monthly a) and seasonal b) averaged alongshore currents from upper level current meters at Keys shelfbreak current meter moorings and Sand Key CMAN alongshore wind stress for 5-year period April 1989–April 1994.

IMPLICATIONS FOR LARVAL TRANSPORT — THE RECRUITMENT CONVEYOR.—The combination of the above mentioned physical processes tends to form a recirculating retention and recruitment pathway for pelagic larvae spawned in the Florida Keys coastal waters or foreign larvae transported from remote sources. This recruitment conveyor system is shown schematically in Figure 7. The four primary physical processes that drive the system are:

(1) *The Florida Current.*—The Florida Current forms the offshore leg of the conveyor. Rapid downstream transport occurs in currents that can reach 200 cm s^{-1}. Larvae can be transported great distances from remote upstream sources in the eastern Gulf of Mexico and Caribbean Sea. This can be particularly significant for species with long pelagic larval stages, such as spiny lobster (*Panulirus argus)* larvae that can remain in the plankton stage for 6 to 12 mo (Lewis, 1951; Sims and Ingle, 1966). The shoreward front of the Florida Current is an area of nearsurface current convergence. Therefore, slow swiming larvae such as fish and lobster larvae and their planktonic food source will tend to be concentrated together in the frontal zone (Yeung, 1996). Onshore meanders of the front

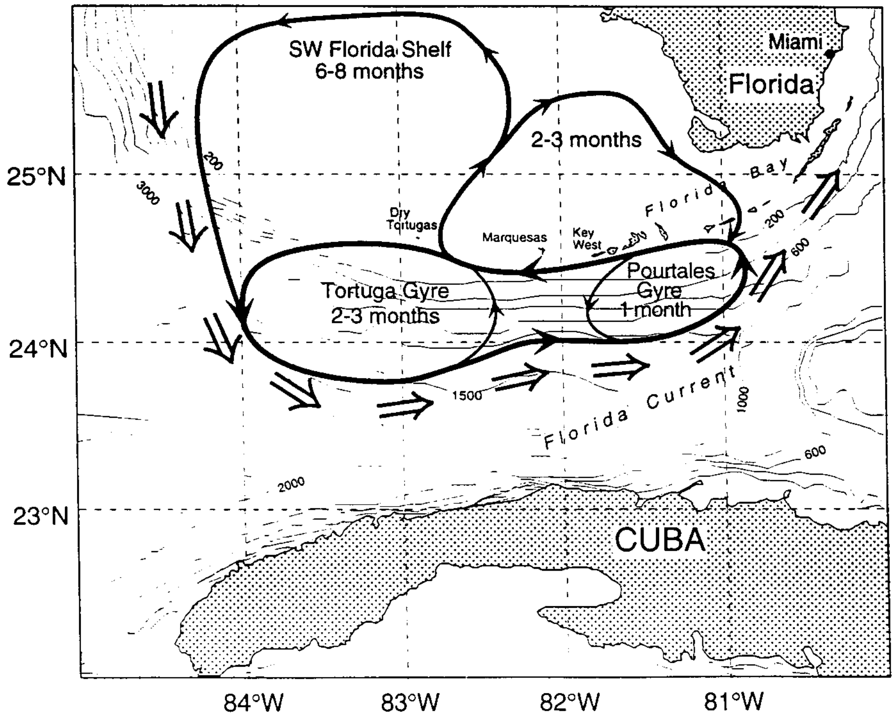

Fig. 7. Schematic of possible recruitment pathways for locally spawned fish and lobster larvae in the lower and western Florida Keys.

will transport larvae closer to the coastal zone and settlement habitat. Also the mean shoreward displacement of the front in the middle and upper Keys will carry larvae closer to settlement habitat in this region. Larval detrainment from the front to the coastal zone can occur through small-scale cross-frontal mixing, eddy circulations and surface Ekman transports. Increased abundances of lobster and conch larvae have been observed near the outer reefs when the Florida Current front was located in a nearshore position (Yeung, 1996; Stoner, Mehta and Lee, 1997). Eddy circulations in small-scale frontal eddies and Tortugas gyres have been shown to aid exchange of Florida Current and coastal species of fish larvae and pink shrimp larvae (Limouzy-Paris et al., 1996; Criales and Lee, 1995).

(2) *The Tortugas Gyre.*—The cyclonic circulation of the Tortugas gyre and its evolution into smaller gyres in the lower Keys provides a mechanism to entrain newly spawned larvae that can be retained in the gyre for up to several months or escape the gyre on one of its shoreward circuits (Lee et al., 1994). Pink shrimp larvae have been shown to take advantage of this pathway (Criales and Lee, 1995). The Tortugas gyre also enhances food availability through upwelling responses and concentration of microzooplankton (Lee et al., 1992; 1994).

(3) *Shoreward Ekman Transports.*—Onshore surface Ekman transports prevail throughout the region from the Dry Tortugas to the middle Keys due to persistent westward winds and east-west orientation of the coastal zone in this region. Spiny lobster larvae tend to be distributed in the upper mixed layer above the thermocline (Yeung and McGowan, 1991; Yeung et al., 1993), where onshore Ekman transports in the upper layer can result in

concentration in the Florida Current front and detrainment into the coastal zone. Shoreward Ekman transports are further enhanced near the Florida Current axis, where surface currents and winds are opposed, significantly increasing the surface stress and onshore Ekman transport (Rooth and Xie, 1992) and resulting in concentration of larvae along the front or in the interior of a coastal gyre.

(4) *Coastal Countercurrent.*—The westward flowing coastal countercurrent described above as resulting from the combined influences of downwelling winds and coastal gyres provides the primary return leg of the recruitment conveyor. This feature can extend from the middle Keys to the Dry Tortugas. Its northern extent is limited by the curving coastline that cause the prevailing westward winds to change from an alongshore orientation in the lower Keys to onshore in the upper Keys. The maximum northward penetration of the countercurrent occurs in the fall when southwestward winds prevail. These winds are oriented alongshore in the middle Keys, and have a southward component in the upper Keys, which could result in a countercurrent extending the entire length of the Keys from the Dry Tortugas to Key Largo. As shown here, the coastal countercurrent is prevalent in the outer shelf, seaward of the reef tract, but is also believed to extend shoreward to Hawk Channel and the nearshore waters (Lee, 1986; Pitts, 1994). Cross-shore flows in the countercurrent are onshore in the upper layer and offshore in the lower layer in the lower Keys due to an Ekman response to the westward winds. However the cross-shelf flow shifts to offshore in the Dry Tortugas region due to influence from the cyclonic circulation in the gyre. This gyre circulation also appears to cause a westward intensification in the countercurrent. Larvae that become detrained from the Florida Current front will be transported westward and shoreward by the coastal countercurrent, providing ample opportunity for recruitment to the reefs and nearshore zones.

Because of the variable nature and mix of processes that form the recruitment conveyor system larvae are provided with many opportunities for recruitment into the Keys on time scales ranging from days to months. Recruitment pathways providing even longer retention times, such as required by spiny lobster larvae, are also available and are shown schematically on Figure 7. These require movement onto the southwest Florida shelf and return to the Keys via either the Loop Current or by way of a mean southeastward flow through western Florida Bay and eventually entering the coastal countercurrent in the middle or lower Keys. The west Florida shelf/Loop Current pathway has been observed with satellite tracked drifters and can increase larvae retention to 8 mo (Lee et al., 1994). The western Florida Bay/coastal countercurrent route is also quite plausible as shown by trajectories of surface drifters recently deployed west of Florida Bay (Lee et al., 1996), and observations of net southeastward flow through the tidal channels between the Keys (Smith, 1994).

Seasonal changes in the conveyor system may also influence seasonal patterns in recruitment. The seasonal maximum in westward and southwestward alongshore winds in the fall can cause a seasonal maximum in the strength and northward extent of the coastal countercurrent, together with a maximum in onshore surface Ekman transports and a minimum in Florida Current downstream flow. These consequences should result in greater larval retention and enhanced opportunity for recruitment into the Keys coastal waters. During summer months winds are weak and have a northward component, and the Florida Current flow is maximum, causing the coastal countercurrent to reverse to eastward or northeastward flow. The result could be a decrease in recruitment to the Keys as larvae are carried out of the coastal retention zone by the Florida Current.

CONCLUSIONS

The data presented here, when viewed together with results from previous studies (Lee, 1986; Pitts, 1994), indicate that the Atlantic coastal waters of the Florida Keys consists of two distinct flow regimes: the nearshore region out to and including Hawk Channel, where current variability is primarily controlled by tidal and wind forcing; and the outer shelf, seaward of the reef tract, where current variations are caused by a mix of wind and Florida Current forcing from the transient occurrence of gyres, eddies and meanders. In this paper we are mostly concerned with the outer shelf. However, the current response to local wind forcing extends across the shelf. Similar to other continental shelves, the Keys coastal waters respond energetically to alongshore wind forcing and only weakly to cross-shore winds. The response to alongshore winds consists of a barotropic alongshore current and Ekman cross-shore currents that are out of phase in the upper and lower layers. Because of the curving coastline of the Keys island chain, in the presence of a prevailing westward zonal wind, the region from Dry Tortugas to the middle Keys constitutes a downwelling coast on the mean. This results in a westward mean coastal countercurrent, with speeds ranging from -2 cm s^{-1} at Looe Reef to -8 cm s^{-1} at Dry Tortugas. The upper Keys, oriented in a more north/south direction, are characterized by onshore winds on the mean that result in a weak northward mean flow without significant cross-shelf Ekman transports. This response is observed in Hawk Channel off Key Largo (Lee, 1986; Pitts, 1994). However, at the outer shelf off Key Largo, a strong northward mean baroclinic flow of 20 cm s^{-1} occurred near the surface with a significant onshore component due to the close proximity to the Florida Current front. The Florida Current converges shoreward in the upper Keys following its northward turn in the middle Keys. Cyclonic gyres have been observed to develop over the slope off the Tortugas and decrease in size and duration as they migrate to their demise in the middle Keys (Lee et al., 1992; 1994). Near the Tortugas these features can persist for several months and appear to cause a mean westward intensification of the coastal countercurrent. These gyres can influence flows in the lower Keys over time scales of 2 to 4 wks, but are rarely observed in the middle and upper Keys where the primary mode of Florida Current influence on coastal current variability occurs from weekly period meanders and frontal eddies. Thus the coastal waters of the middle Keys appear to be a transition region between a wind- and gyre-dominated domain in the lower to western Keys and a Florida Current- and frontal eddy-dominated domain in the upper Keys. Due to this transition, the outer shelf of the middle Keys becomes a zone of strong divergence of alongshore flow, westward in the lower Keys and northward in the upper Keys. Compensation for the flow divergence may occur from strong onshore mean flows near Tennessee Reef and also from a net southeastward flow from the Gulf of Mexico and Florida Bay observed through the Keys passages by Smith (1994) and Lee et al. (1996).

The annual variability of outer shelf currents in the Keys appears to be directly influenced by annual cycles of alongshore wind and Florida Current volume transport. Monthly and seasonal means at all outer shelf sites show seasonal maximum upstream flow with Ekman-like onshore (offshore) transports in the upper (lower) layers occurred during the fall season of maximum upstream winds (westward in lower Keys and southwestward in upper Keys). However, during the summer when wind forcing was weak and during the spring semi-annual maximum of upstream winds, the alongshore currents were downstream and coincident with the annual maximum downstream volume transports of the

Florida Current. The annual temperature cycle in the near surface waters at the outer shelf off Looe Reef shows a maximum monthly mean of about 30°C in August and an minimum of about 24°C from January to March. The annual temperature cycle appears to follow the seasonal cycle of local air temperature. Stratification was strongest during spring and summer seasons and weakest during fall.

The combination of downstream transport in the Florida Current, onshore Ekman transports along the downwelling coast, upstream flow in the coastal countercurrent and recirculation in the Tortugas gyre forms a recirculating recruitment pathway stretching from the Dry Tortugas to the middle Keys that enhances larval retention and recruitment into the Keys coastal waters of larvae spawned locally or foreign larvae from remote upstream areas of the Gulf of Mexico and Caribbean Sea. Convergences in the Florida Current front and coastal gyres provide a mechanism to concentrate foreign and local larvae, as well as their planktonic food supply. Onshore Ekman transports and horizontal mixing from frontal instabilities enhance export from the oceanic waters into the coastal zone. A wind- and gyre-driven coastal countercurrent provides a return leg to aid larval retention in local waters. Seasonal cycles of the winds, countercurrent and Florida Current favor recruitment to the coastal waters during the fall when the countercurrent can extend the length of the Keys from the Dry Tortugas to Key Largo, onshore Ekman transports are maximum and downstream flow in the Florida Current is minimum. The mix and variability of the different processes forming the recruitment conveyor provide ample opportunity for local recruitment of species with larval stages ranging from days to several months. For species with longer larval stages, such as the spiny lobster which has a 6 to 12 mo larval period, a local recruitment pathway exists through the southwest Florida shelf and return via the Loop Current and the Keys conveyor system. Return from the southwest Florida shelf could also occur through western Florida Bay and the Keys coastal countercurrent, due to a net southeastward flow recently observed connecting the Gulf of Mexico to Atlantic through the Keys (Smith, 1994; Lee et al., 1996).

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