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AN INVESTIGATION OF NEAR-BOTTOM FLOW PATTERNS ALONG AND ACROSS HAWK CHANNEL, FLORIDA KEYS

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ABSTRACT

Current and wind data collected during a 124-day study period between August and December of 1991 as part of the SEAKEYS program are used to characterize near-bottom circulation at two study sites widely separated along the longitudinal axis of Hawk Channel, Florida Keys. Currents at both study sites are influenced primarily by local winds and secondarily by the tides. Spectral analysis indicates statistically significant coherence between along-channel wind stress and currents at periodicities of 3–4 days. Tidal co-oscillations are responsible for 17–19% and 5–25% of the total variance of the along-channel and across-channel currents, respectively. Net flows appear to reflect seasonal changes in local winds. During the first half of the study net flow is towards the northeast at a resultant speed of 0.4 $cm \cdot s^{-1}$ at the Upper Keys site and towards the south, southwest at 2.3 $cm \cdot s^{-1}$ at the Lower Keys site. During the second half of the study net flow is towards the southwest at both locations, with resultant speeds of 1.0 $cm \cdot s^{-1}$ at the Upper Keys site and 6.1 $cm \cdot s^{-1}$ at the Lower Keys site. Evidence suggests that divergence may be occurring throughout the study period. Net inflow to Hawk Channel through tidal channels supports the idea of a divergence in the along-channel flow and probably explains a distinct across-channel motion at the Lower Keys site.

Hawk Channel lies between and parallels the Florida Keys and the Florida reef tract 8–10 km off shore on the Atlantic Ocean side of the island chain. The channel is typically 3–6 km wide, 5–15 m deep and extends approximately 240 km from Key Biscayne to just west of Key West. Over the last few years there has been a growing interest in transport processes occurring along and across Hawk Channel. Larval transport across Hawk Channel from spawning grounds on the reef to nursery areas in the shallow grass beds and mangrove forests near the Keys is important to the ecology of this region. During the early 1980's attention was directed towards the concept that cold Florida Bay water moving through tidal channels limited the development of hard corals along the reef tract (Roberts et al., 1982, 1983; Walker et al., 1982, 1987). More recently, there has been growing concern that the corals of the reef tract are in danger of being displaced by marine algaes through eutrophication processes (LaPointe and O'Connell, 1990; LaPointe and Clarke, 1992). This theory holds that nutrient concentrations in waters surrounding the reefs, originating from anthropogenic sources from the Keys and/or Florida Bay and moving across Hawk Channel to the reefs, may be increasing allowing algaes to become established in an otherwise nutrient poor environment.

Investigations of the circulation patterns of Hawk Channel have been limited. Lee's (1986) work in the early 1980's showed that near-bottom currents in the shallower regions of Key Largo National Marine Sanctuary in the Upper Keys (including Hawk Channel) were controlled by the tides and atmospheric forcing. The data indicated that flow in Hawk Channel had a seasonal cycle that appeared to follow changes in local wind patterns. Along-channel flow to the south, towards Key West, was characteristic of fall and winter. Northerly flow was more common during spring and summer. Current data collected between 1986 and 1988 from Hawk Channel at Looe Key National Marine Sanctuary (LKNMS) in the Lower Keys also showed a seasonal pattern (LaPointe et al., 1992). Resultant along-

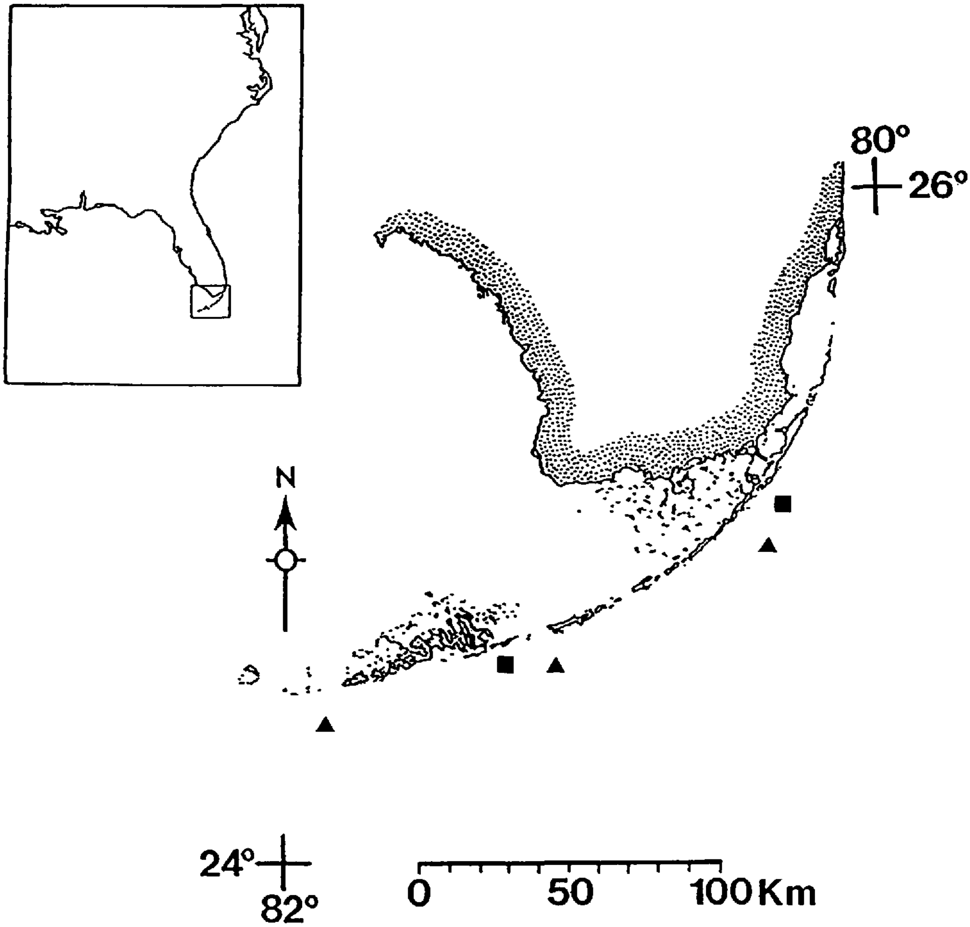

Figure 1. Study sites along Hawk Channel, Florida Keys. Squares represent the locations of the current meters and triangles indicate the NOAA C-MAN weather stations.

channel transport during fall and winter months was towards the west, southwest. However, spring and summer transport showed a pattern dominated by low-frequency reversals; flow to the northeast alternated with movement to the west.

Both of the above studies were limited in geographic scope; one being confined to the Upper Keys and the other to the immediate vicinity of LKNMS in the Lower Keys. My purpose in this paper is to compare tidal and wind-driven near-bottom flow at two study sites widely separated along the longitudinal axis of Hawk Channel. The study represents an attempt to characterize circulation over a larger segment of this channel than has been previously considered.

Data and Methods

Current speeds and directions were recorded hourly using two General Oceanics, Inc. Model 6011 Mark-I inclinometer-type, solid state recording current meters (½° tilt and 2° directional accuracy). One of these was moored 2 m above the bottom in 7 m of water approximately midway between Key Largo and Dixie Shoal in the Upper Keys at 25°05.2′N, 80°20.6′W (Fig. 1). The second instrument was moored 4 m above the bottom in 12 m of water 5.8 km due south of Bahia Honda Key in the Lower Keys at 24°36.4′N, 81°16.7′W. The instruments were positioned close to the bottom to reduce wave noise and the probability that they would be seen from the surface. Also, sampling the lower part of the water column makes comparisons with the earlier studies more valid.

Wind data from the same time period, recorded by R. M. Young anemometers attached to NOAA C-MAN weather stations at Molasses Reef in the Upper Keys, Sombrero Reef in the Middle Keys, and Sand Key in the Lower Keys, were obtained through the Florida Keys Marine Lab. Sixty 1-min wind speed and direction observations were vector averaged internally to provide hourly samples. The anemometer on Sombrero Reef was the closest to the current meter off Bahia Honda Key, but it malfunctioned during the first 6 weeks of the study. The next closest C-MAN station was on Sand Key so data from this location were utilized for the early part of the study period.

Several analytical techniques were used to quantify the magnitudes and relative importance of tidal and low-frequency forcing in producing the observed circulation patterns. Hourly current vectors were plotted head-to-tail as progressive vector diagrams to characterize transport over time scales of days to months. The tidal components of the total along-channel and across-channel current were isolated by harmonic analysis of 29-day segments of data as described by Dennis and Long (1971). Since the time series were substantially longer than 29 days, multiple harmonic analyses were performed using 29-day segments of data successively offset in time by 1 week. The individual pairs of harmonic constants (amplitudes and phase angles) were then vector-averaged (Haurwitz and Cowley, 1975), to provide a mean amplitude and phase angle. A measure of the relative importance of the tide was obtained by calculating the percent of the total variance explained by the principal tidal constituents. The percent of the total variance of the along-channel and across-channel components due to the tides is given by:

$$P_T = 100\left[\left(\frac{1}{2}\sum_{i=1}^{n} A_i^2\right)\Big/V_T\right], \qquad (1)$$

where n is the number of tidal constituents, A is the amplitude of the i^{th} tidal constituent and V_T is the total variance in the along-channel or across-channel current (Panofsky and Brier, 1963).

Wind data were converted to wind stress vectors using the method described by Wu (1980) for moderate wind speeds (1–20 $m \cdot s^{-1}$). The north-south and east-west wind stress components were used to construct progressive vector diagrams for comparisons with the currents.

To determine the relationship between wind stress and currents, high-frequency variability, including tides and sea-breeze effects, was removed from each time series using the "D39" Doodson-Warburg low-pass filter (Groves, 1955). Over the frequency band of 0.025–0.030 cph this filter removes 75–88% of the variance in the input time series. Energy density spectra for filtered wind stress and filtered currents were computed for each of the study sites along with the associated coherence and phase spectra (Little and Shure, 1988).

Results

Figure 2 shows a composite of the progressive vector diagrams of wind stress from the Molasses Reef C-MAN station (top plot) and near-bottom currents recorded at the nearby Hawk Channel study site off Key Largo (bottom plot). Probably the most striking feature in the two plots is the abrupt change in both the magnitude and direction of movement beginning in early October. The bottom plot shows that for the first 7 weeks of the study flow is approximately along-channel to the northeast at a resultant speed of 0.4 $cm \cdot s^{-1}$. From the middle of September through to the end of the record the curve indicates a predominately along-channel flow towards the southwest at a resultant rate of 1.0 $cm \cdot s^{-1}$. Note that there are occasional periods when the current indicates temporary reversals or erratic movement with little displacement. This is most apparent through August and September and near the end of the record.

Harmonic analysis indicates that tidal currents at the study site are very weak (Table 1). The amplitude of the principal tidal constituent, M_2, of the along-channel current component is 1.5 $cm \cdot s^{-1}$; the across-channel component has an M_2 amplitude of only 0.3 $cm \cdot s^{-1}$. Although the tidal constituent amplitudes appearing in Table 1 are small and within the accuracy of the instrument, they are probably real because harmonic analyses indicate relatively constant phase angles for each constituent. Overall, the tides account for 19% and 5% of the total variance in the along-channel and across-channel currents, respectively. This is

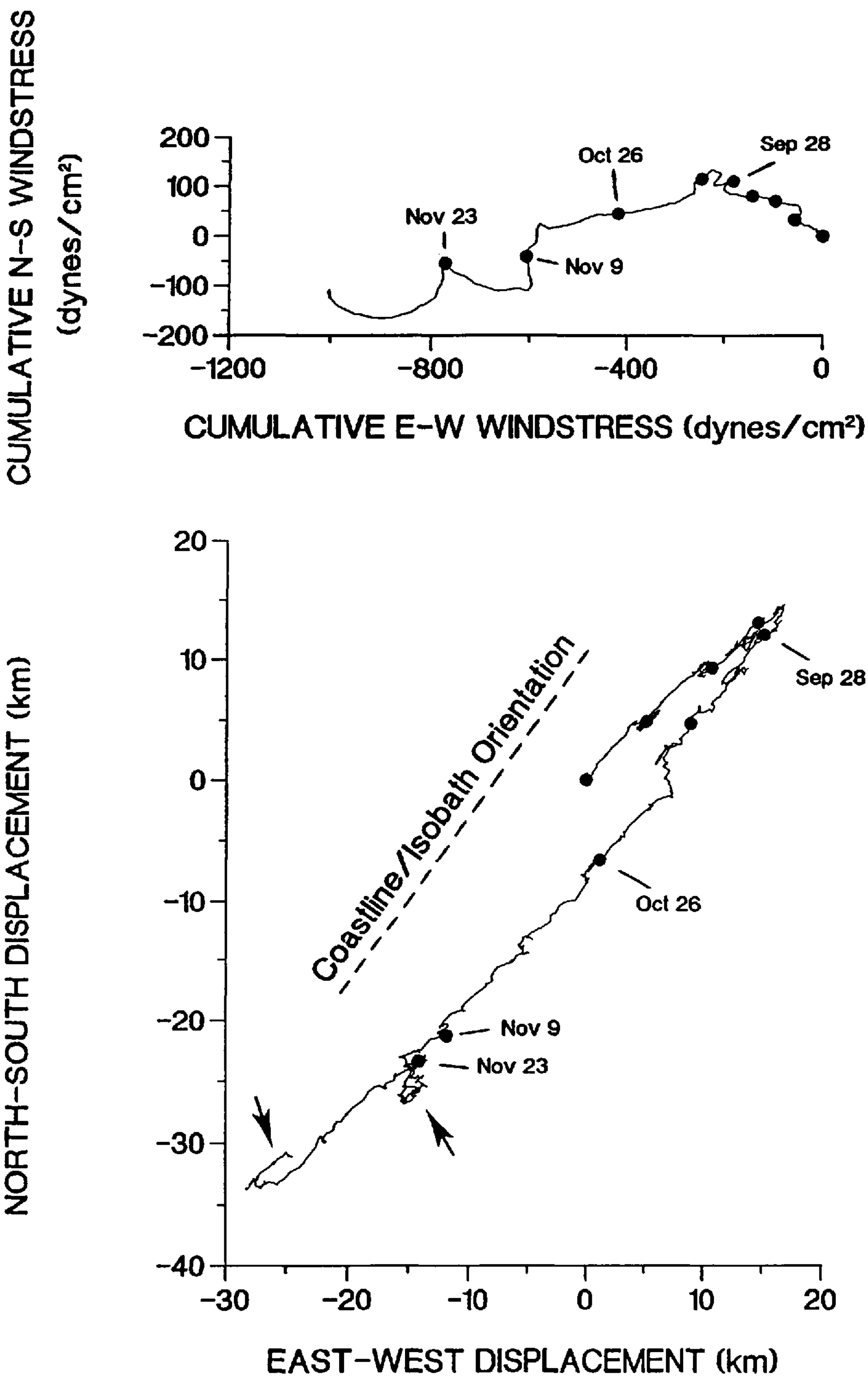

Figure 2. Composite of the progressive vector diagrams of wind stress at Molasses Reef (top) and water currents recorded off Key Largo (bottom) 3 August–4 December 1991. Solid circles are spaced 2 weeks apart. The orientation of coastline/isobaths is indicated by hatched line. Arrows in the bottom plot indicate temporary reversals in currents which correspond in time with significant changes in winds.

Table 1. Harmonic constants (amplitudes, η, in cm s^{-1} and phase angles, ϕ, in degrees) of principal tidal constituents of along- and across-channel current components at two study sites in Hawk Channel, Florida Keys. The percent of the total variance in the currents due to the tides (P_T) is provided.

	Hawk Channel off Key Largo				Hawk Channel off Bahia Honda Key			
	Along-channel		Across-channel		Along-channel		Across-channel	
	η	ϕ	η	ϕ	η	ϕ	η	ϕ
M_2	1.5	024	0.3	353	2.5	108	2.6	027
K_1	1.0	319	0.4	297	1.5	039	0.4	025
O_1	0.9	300	0.3	287	2.0	014	0.5	037
N_2	0.5	007	0.1	308	0.9	097	0.6	006
S_2	0.3	101	0.1	060	0.5	170	0.9	048
P_1	0.3	319	0.1	297	0.5	039	0.1	025
P_T	19%		5%		17%		25%	

consistent with Figure 2, which shows little or no evidence of rotary tidal ellipses in the curve.

The progressive vector diagram of the wind stress, calculated from the Molasses Reef C-MAN station data, indicates that for the first 8 weeks of the study winds are relatively weak and from the east-southeast, or almost directly onshore (the resultant winds are directed toward 297° while the orientation of coastline/isobaths in the vicinity of the study site is 042°–222°). The curve shows a distinct shift beginning in early October and for the next 2 months resultant wind stress is from the northeast with a four-fold increase in magnitude. The pattern during the second half of the study appears more erratic than that observed for the first 2 months. Persistent northeasterly wind from mid October through the first week of November is followed by winds directly out of the north, probably indicating the passage of the season's first cold front. The record suggests the passage of

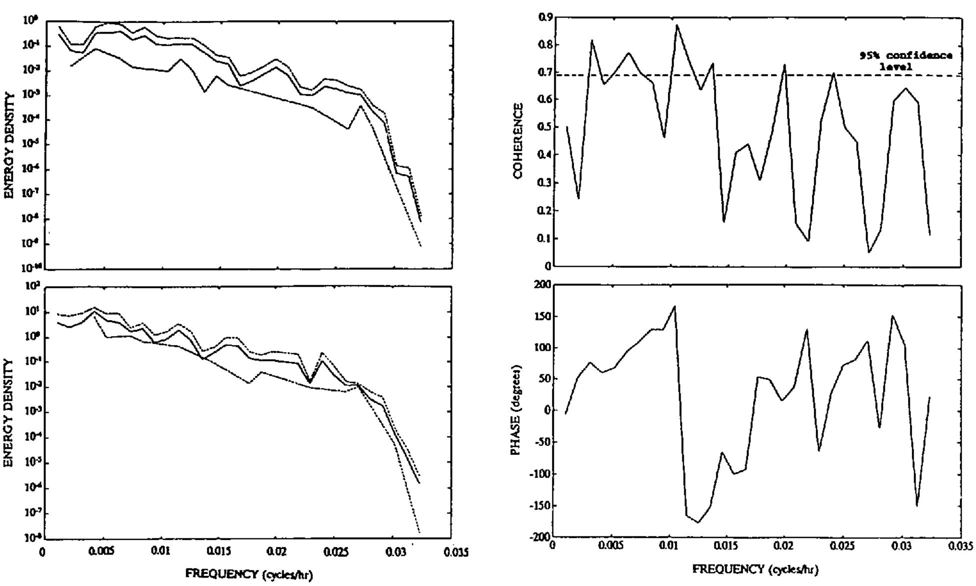

Figure 3. Energy density, coherence and phase spectra of low-pass filtered along-channel wind stress and currents from the Upper Keys sites. Hatched lines represent 95% confidence limits.

another cold front during the fourth week of November. After the fronts have moved through the region the wind veers to the east, southeast for several days.

Results of the spectral analysis indicate a relatively flat energy density spectrum for both the along-channel wind stress and currents over the frequency band of 0.001 to 0.027 cph (Fig. 3). There are no clearly defined spectral peaks. Energy density decreases substantially at frequencies greater than 0.027 cph due to filtering effects. Coherence significant at the 95% confidence level is apparent at frequencies of 0.004–0.007 cph (5–12 d) and 0.010–0.013 cph (3–4 d). The phase spectrum indicates that over the 0.003–0.014 cph frequency band (3–12 d periodicities) the phase lead of wind stress over currents generally increases from 60° to 210° as frequency increases. Thus, wind stress forcing has a relatively constant time lead of 36–48 h over near-bottom currents at periodicities greater than 3 d.

Figure 4 shows a composite of the progressive vector diagrams of the wind stress from Sand Key and Sombrero Reef C-MAN stations (top plot) and near-bottom currents from the Hawk Channel study site off Bahia Honda Key (bottom plot). The orientation of the coastline/isobaths has rotated clockwise approximately 45°. The early October change in wind and current at Key Largo is apparent at this location as well. The bottom plot shows that for the first 10 weeks of the study displacement is predominately offshore with quasi-periodic reversals in the along-channel component. The resultant current speed during this time is 2.3 $cm \cdot s^{-1}$ at a resultant heading of 190°. From early October through the first 9 days of November displacement shows a pronounced and consistent along-channel movement to the southwest. Following a temporary flow to the southeast at the end of the second week in November currents resume a predominately along-channel heading towards Key West but with a significant offshore deflection. The resultant current speed during the second half of the study period is 6.1 $cm \cdot s^{-1}$ at a resultant heading of 225°. Note that the cumulative displacement at this location is an order of magnitude greater than at the Upper Keys site.

A harmonic analysis indicates M_2 amplitudes of 2.5 $cm \cdot s^{-1}$ for the along-channel current component and 2.6 $cm \cdot s^{-1}$ for the across-channel component (Table 1). The tides account for 17% and 25% of the total variance in along-channel and across-channel currents, respectively.

The progressive vector diagram of the wind stress from the Lower Keys is almost identical to that observed from the Upper Keys. Note that the southeast wind during the first half of the study period is not directly onshore at this location as it is in the Upper Keys (due to the orientation of the coastline/isobaths), but strikes the coast at an angle of approximately 40°. Relatively weak wind stress from the southeast is followed by an apparent seasonal change beginning in early October when wind stress increases in magnitude and is predominately out of the northeast. The time series indicates that the Lower Keys also experienced the cold front events in November.

The energy density spectra of along-channel wind stress and currents is similar to that observed at the Upper Keys location (Fig. 5). High coherence between the two time series, significant at the 95% confidence level, occurs primarily at frequencies of 0.011–0.014 cph (3–4 d). The phase spectrum indicates wind stress leading currents by approximately 0.5–3 d at these periodicities. Since the currents at this location demonstrate a significant across-channel component, spectral analyses were performed for low-pass filtered, across-channel wind stress versus across-channel currents and along-channel wind stress versus across-channel currents (not shown). No clear indication of coherence is indicated between

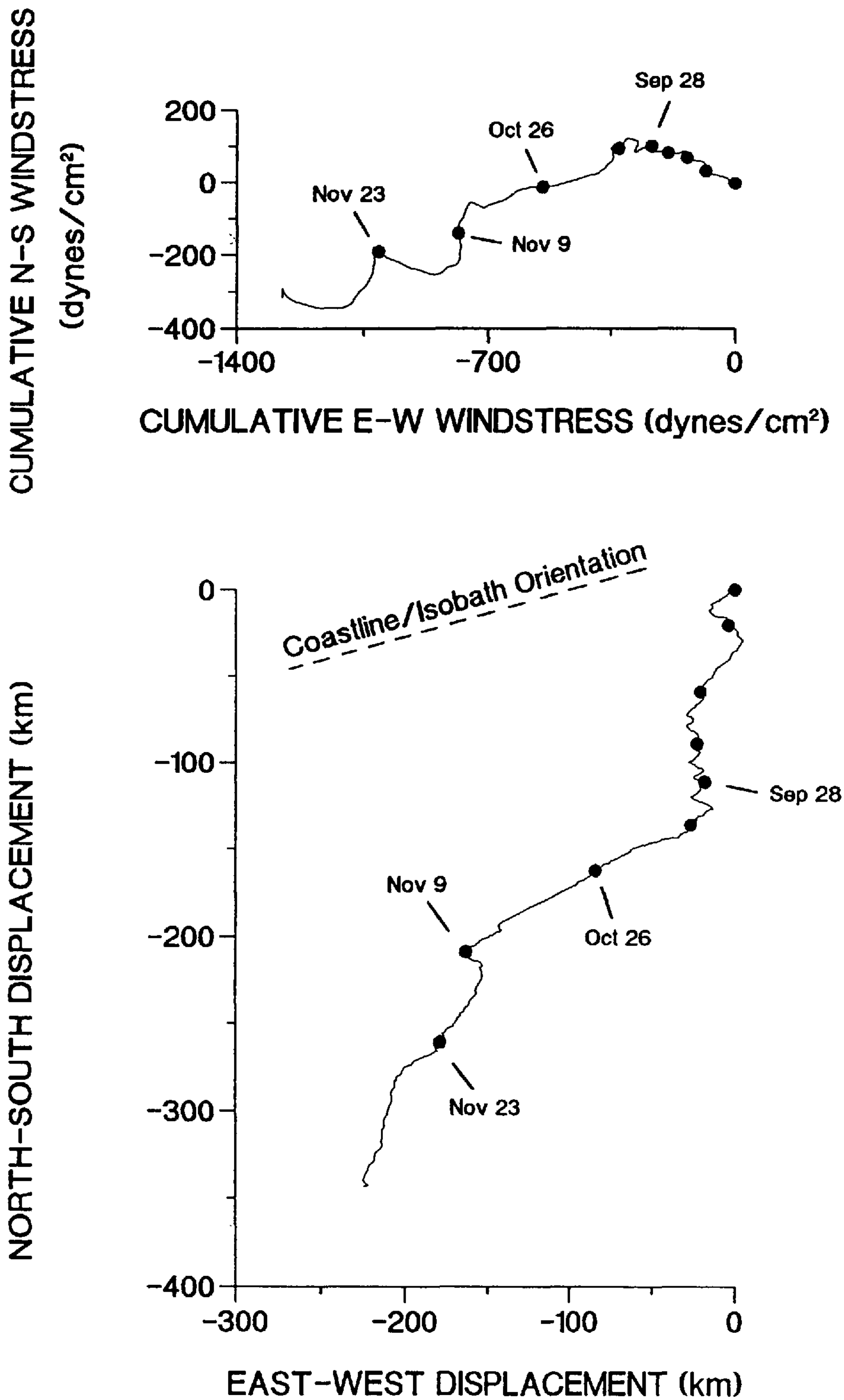

Figure 4. Composite of the progressive vector diagrams of wind stress at Sand Key and Sombrero Reef (top) and currents recorded off Bahia Honda Key (bottom) 3 August–4 December 1992. Solid circles are spaced 2 weeks apart. The orientation of coastline/isobaths is indicated by hatched line.

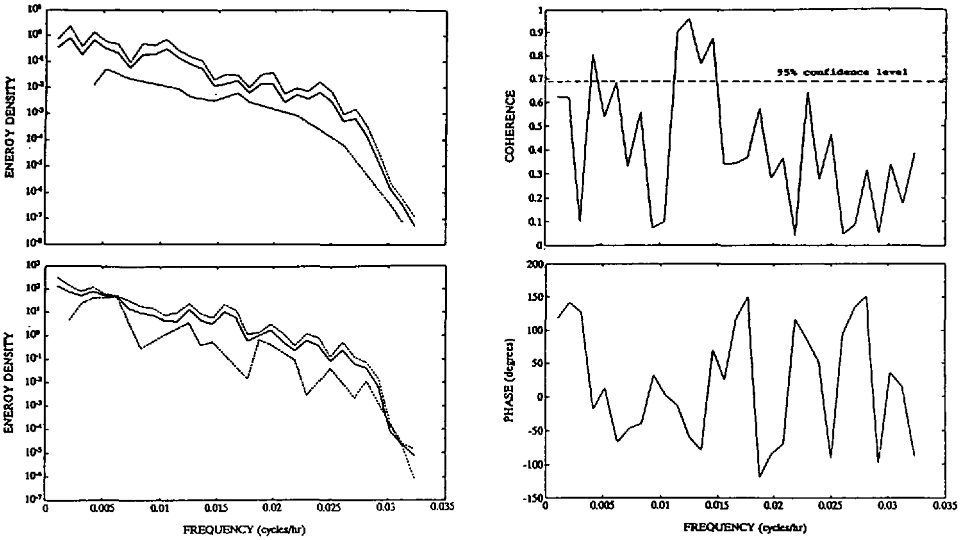

Figure 5. Energy density, coherence and phase spectra of low-pass filtered along-channel wind stress and currents from the Lower Keys sites. Hatched lines represent 95% confidence limits.

across-channel wind stress and across-channel currents. However, the across-channel current is coherent with along-channel wind stress at the 95% confidence level at frequencies of 0.013–0.018 cph (2.5–3 d). The phase spectrum indicates a phase lead of wind stress over currents of 1–2.5 d.

Discussion

The seasonal pattern observed in the near-bottom currents at the study site off Key Largo is very similar to that shown by Lee (1986) for the same region. However, the mean along-channel flows he reported were larger in magnitude (1–4 $cm \cdot s^{-1}$ in summer and 2–5 $cm \cdot s^{-1}$ in winter) than those recorded in this study. Also, Lee reported that the tides play a significant role in controlling the currents. His data showed that 80% of the total cross-shelf variance and 50% of the total along-shelf variance was due to fluctuations in the tidal/inertial band. The data in this study indicate that the tides play a comparatively minor role when compared to the low-frequency forcing mechanisms. Residual tidal transport was not investigated, but in view of the small amplitudes it is unlikely that tidal residual motion would be significant.

The circulation pattern off Bahia Honda Key is similar to that observed in the same region during the fall and winter months of 1987–88 (LaPointe et al., 1992); both studies show steady along-channel flow towards Key West. However, the two studies reveal distinctly different current patterns during the summer months. Whereas in the earlier study flow to the northeast alternates with movement to the west, this study indicates a pattern dominated by offshore movement to the south with periodic reversals in the along-channel component. The only common feature between the current records during this season is the occurrence of low-frequency reversals. Although wind forcing was not explored for the earlier study, one possible explanation for the observed differences in summer current patterns between these two studies is wind.

Qualitatively, the cause and effect relationship between wind stress and currents off Key Largo seems clear. When wind is out of the southeastern quadrant, as it is during the first 7 weeks of the study, along-channel displacement is towards the northeast. Even in the latter part of the study when the wind stress is out of the southeast for only a few days following what are apparently frontal passages, the relationship appears again (indicated by the arrows in the bottom plot of Fig. 2). During the second half of the study, predominately northeast and north winds correspond in time with increased along-channel currents in the downstream direction.

The coupling of wind stress and near-bottom currents in the Lower Keys is not as clearly defined as for the Upper Keys location, although there appears to be a general pattern. For the first half of the study relatively light southeast winds correspond in time to an offshore current deflection with irregular reversals in the along-channel movement. As the wind swings around to the northeast and increases in strength near the end of October the flow in the channel shows a corresponding change to a downwind direction and an increase in speed.

While the north and northeast winds characteristic of the second half of the study appear to produce similar flow patterns at the two study sites, the greatest difference in resultant flow occurs during late summer when southeast winds prevail: flow to the northeast at the Upper Keys study site and offshore movement to the south at the Lower Keys site. One explanation for the pattern observed in the Upper Keys during this time is the natural tendency for southeast winds to drive a northward current in Hawk Channel. This is supported by the coincidence of southeasterly winds and northerly flow during two time periods near the end of the study period, as well as by the results of the spectral analysis. Lee (1986) observed the same relationship in his study.

The pronounced across-channel flow recorded at the Bahia Honda site was investigated as a response to wind stress forcing. The lack of coherence between across-channel wind stress and across-channel flow indicates that a near-bottom return flow forced by onshore winds is not occurring. However, the high coherence and phase relationship between along-channel wind stress and across-channel currents suggests a near-bottom return flow of shoreward-directed Ekman transport.

An alternative to wind forcing is the possibility that the seaward deflection of near-bottom currents is a response to exchanges between the Gulf of Mexico and the Atlantic Ocean. Current data recorded in Bahia Honda Channel indicated a quasi-steady, nontidal net displacement of 620 $m^3 \cdot s^{-1}$ from the Gulf to the Atlantic (Smith, 1994).

A net import of water into Hawk Channel through tidal channels may have two important effects on transport along and across Hawk Channel. First, it helps force a seaward deflection observed at the Lower Keys study site. The magnitude of the across-channel current component in Hawk Channel may depend upon location along the longitudinal axis of the channel. Specifically, those areas of Hawk Channel in close proximity to major tidal channels connecting Florida Bay or the Gulf of Mexico with the Atlantic are likely to experience a greater degree of across-channel transport than elsewhere. In this study the Upper Keys site was over 25 km from the nearest tidal channel and the across-channel current component was very small. The Lower Keys study site, however, was only about 5 km from a tidal channel and the across-channel component was much more distinct. As most of the major connecting channels occur in the Middle and Lower Keys, across-channel transport is probably more significant in these areas.

Secondly, the net flow through tidal channels may produce or increase divergence of the flow along the longitudinal axis of Hawk Channel. Divergence is easy to visualize during the first 2 months of the records when displacement is in opposite directions. During the latter half of the study, when displacement at both study sites is in the same direction, divergence is less clear. Volume transport calculations were not made. However, the consistently stronger current speeds recorded at the Bahia Honda site coupled with the evidence of a net inflow to Hawk Channel indicates that divergence is likely.

In conclusion, the data tend to support findings from earlier work in Hawk Channel, particularly the wind-driven seasonal pattern of along-channel transport. Across-channel movement, while minimal at the Upper Keys study site, appears to play an important role in net transport at the Lower Keys study site probably due, at least in part, to a local net inflow from the Gulf of Mexico and a near-bottom return flow of shoreward-directed Ekman transport. Tidal currents are relatively weak and probably of negligible importance to long-term net transport. Finally, although not conclusive, evidence strongly suggests current divergence occurring throughout the study period.

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