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Near-Shore Circulation in the Lower Florida Keys

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ABSTRACT

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Current meter data from three study sites are used to describe a clockwise re-circulation of near-shore waters in the lower Florida Keys. An 11-month record from Northwest Channel, the main channel connecting gulf and Atlantic waters just west of Key West, indicates a long-term net Atlantic-to-gulf flow that averaged 4.5 cm s^{-1}. Tidal co-oscillations dominated the instantaneous current in the channel, accounting for 95% of the total variance in along-channel flow. By comparison, low-frequency fluctuations through the channel were generally 5–20 cm s^{-1} over time scales of several days. Data from a study site in the Gulf of Mexico just north of the Content Keys indicate that tidal and low-frequency along-isobath motions dominated across-isobath flow, but resulted in little net along-shelf displacement during a 5-month study. By comparison, the direction of the weaker across-isobath current was more consistent and resulted in a net shoreward near-bottom flow that averaged about 1 cm s^{-1}. Results from a 13-month study in Atlantic shelf waters just south of Bahia Honda Key showed a long-term net along-isobath flow to the southwest, toward Key West, that averaged 3.5 cm s^{-1}. Across-isobath currents were significantly weaker, but showed a net seaward movement of 1.8 cm s^{-1}. Spectral analysis indicates that winds from the eastern quadrant were most responsible for driving water past all three study sites, and accounted for the long-term flow observed in Hawk Channel and Northwest Channel. Long-term shoreward near-bottom flow north of the Content Keys was generally upwind.

ADDITIONAL INDEX WORDS: *Florida Keys, long-term flow, wind stress forcing, tidal currents, re-circulation.*

INTRODUCTION

The circulation of Atlantic Ocean waters south of the lower Florida Keys has been described through a number of observational studies conducted over the past ten years. LEE *et al.* (1992, 1994) showed that flow at and seaward of the reef tract is significantly influenced by the passage of cyclonic gyres that develop off the Dry Tortugas and migrate eastward. These gyres, with horizontal dimensions of approximately 200 km in diameter, generally occur over a 30–60 d time scale. Along-shelf wind forcing has also been shown to have a significant influence on circulation of Atlantic shelf waters. Prevailing westward winds, which align with the east-west orientation of the coastline, produce a coastal counter-current south of the western Keys that opposes the Florida Current. LEE *et al.* (1992) also documented downwelling along this section of the coast in response to the persistent westward along-shelf winds. More recently, an onshore Ekman transport in the upper layers and an offshore return flow in lower layers have been reported seaward of the shelf (LEE and WILLIAMS, 1999).

Circulation studies conducted in Hawk Channel—the elongated shallow basin that lies between the Keys and the reef tract and which serves as the continental shelf on the Atlantic Ocean side of the Keys—suggest a quasi-steady, long-term along-shelf flow to the west off the Lower Keys (LAPOINTE *et al.*,1992; PITTS, 1994, 1997). The along-shelf current pattern exhibits a seasonal cycle that follows seasonal changes in the regional wind field. Along-shelf flow to the west is characteristic of fall and winter months when winds are predominantly southwestward, while flow during late spring and summer is more variable as seasonal winds shift to a direction perpendicular to the coastline. One study (PITTS, 1994) reported a near-bottom seaward return flow of Ekman-driven onshore surface currents.

Closer to shore, most of the major tidal channels between Keys have been investigated to determine tidal and long-term exchanges between the gulf and Atlantic sides of the Keys (PRATT and SMITH, 1998; SMITH 1994, 1998, in review). Virtually all of the channels in the Middle and Lower Keys show a net flow out of Florida Bay or the gulf and into the Atlantic. Recent work (SMITH, in review) suggests a close coupling between local wind stress and low-frequency flow through the two largest channels—Long Key and Seven-Mile Bridge channels. Results showed that northwestward wind stress—the prevailing wind direction during the extended summer season—was most effective for driving water through both channels. However, the long-term gulf-to-Atlantic flow is in the opposite direction throughout the year, suggesting that some other mechanism is responsible for driving the observed long-term outflow. Comparison of gulf and Atlantic water level records with time-varying flow through Long Key Channel suggests that persistently higher gulf water levels drive the net outflow (LEE and SMITH, in review).

This paper describes flow patterns in shelf waters on both

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the northern and southern sides of the lower Florida Keys and in Northwest Channel, the main channel connecting Atlantic shelf waters with the Gulf of Mexico just west of Key West. Earlier studies in this region were limited to the Atlantic shelf waters and tidal channels between the Middle Keys. The primary purpose of the paper is to quantify tidal, low-frequency and long-term flow at three study sites in coastal waters of the lower Florida Keys. The role of the local wind field in driving the observed low-frequency flow is also examined.

THE DATA

General Oceanics Model 6011 inclinometers (accurate to ± 1 cm s^{-1} for speed and $\pm 2°$ for direction) were used to measure currents at study sites in shelf waters on the southern and northern sides of the Lower Keys (Figure 1). A 13-month time series was obtained from a site in the middle of Hawk Channel due south of Bahia Honda Key from July 2, 1992 to July 22, 1993. Currents were recorded at a site 5 km north of the Content Keys from Aug. 25, 1999 to Jan. 13, 2000. The Content Keys instrument was moored 2 m above the bottom in 10 m of water while the Hawk Channel current meter was moored 4 m above the bottom in 14 m of water. A second, shorter time series was recorded 10 m above the bottom at the Hawk Channel site from April 14 to May 25, 1993 to determine the extent of vertical current shear. Currents at the upper level were recorded using an Environmental Devices Corporation Model SSM174 impellor-type current meter (± 4 cm s^{-1} speed and $\pm 5°$ directional accuracies). This type of current meter is designed specifically for use in wave-influenced environments.

Current speeds and directions were recorded hourly in Northwest Channel (Figure 1) from Aug. 24, 1999 to Aug. 11, 2000 using a Sontek Argonaut-XR acoustic current meter (accuracies of approximately $\pm 1\%$ of the measured speed and $\pm 2°$ for direction). The current meter was moored at the bottom in 7 m of water and it measured the average current speed from 0.5 m above its transducers (0.8 m above the bottom) to a height of 5 m above the transducers (5.3 m above the bottom).

Meteorological data recorded at NOAA C-MAN stations on Sombrero Reef and Sand Key were obtained through the National Data Buoy Center to investigate the relationship between currents and local wind stress. Wind speeds, wind directions, air pressures and air temperatures were recorded at accuracies of ± 1 m s^{-1}, $\pm 10°$, ± 1 hPa and $\pm 1°$C, respectively. Sixty 1-minute wind speed and direction pairs were vector-averaged internally by the instrument to provide hourly samples. Data recorded on Sombrero Reef were used for comparisons with flow in Hawk Channel and north of the Content Keys. This weather station is 17 km east of the Hawk Channel site and 46 km southeast of the Content Keys site. Weather data from Sand Key were compared with along-channel flow through Northwest Channel. This weather station is located 16 km south of the study site in Northwest Channel.

DATA ANALYSIS

Current vectors were decomposed into along/across-channel or along/across-isobath components. Along-channel current components for Northwest Channel were defined as the headings at which the mean across-channel current component was minimal while maintaining ebb and flood directions 180° apart. Along-channel flow into the gulf is defined as positive. Across-channel motions were very small and not considered further. Along/across-isobath orientation for shelf sites was determined from a close examination of the isobaths depicted on NOAA nautical chart #11442. The along-isobath orientations for the shelf sites near the Content Keys and in Hawk Channel are 060–240° (toward 060° is positive) and 075–255° (toward 075° is positive), respectively. Positive across-isobath flow is seaward on the Atlantic side and shoreward on the gulf side of the Keys. In this paper along/across-isobath is synonymous with along/across-shelf. Shelf site current meters were positioned over a flat bottom with no nearby topographic features (reefs, mud banks) that could steer currents.

To characterize flow past the study site over time scales ranging from days to weeks current components were smoothed with a 40-hr low-pass filter having a half-power point of approximately 37 h (BLOOMFIELD, 1976). To characterize the long-term net movement of water past the study sites the unfiltered instantaneous current values, in cm s^{-1}, were multiplied by the 1-hr time interval they represent, then summed and plotted as cumulative net displacement.

Harmonic constants of the principal tidal constituents (M_2, S_2, N_2, K_1 and O_1) were quantified for the relatively short Content Keys record using a 29-day harmonic analysis program (DENNIS and LONG, 1971). Since the data from this site were substantially longer than 29 days, several overlapping 29-day segments were used, and harmonic constants were vector averaged to obtain values more representative of the entire time series. For the Hawk Channel and Northwest Channel data, harmonic constants were quantified using the least squares harmonic analysis approach (SCHUREMAN, 1958). A measure of the relative importance of the tide was obtained by creating a time series of predicted along/across-isobath or along-channel currents using harmonic constants of the principal tidal constituents, calculating the variance of that time series and dividing it by the variance of the total along/across-shelf or along-channel current components.

To quantify the similarity in the total current at the two levels in the water column at the Hawk Channel site, the complex correlation coefficient was calculated using the method described by KUNDU (1976). This procedure incorporates both along- and across-shelf components of the current at both levels and gives equal weight to each hourly observation for the 6-week overlap of the two time series. The procedure also provides the average deflection of the flow at one level relative to the other.

Wind conditions were described by sorting the data into two-dimensional arrays according to speed and direction. Five speed ranges (increments of 3 m s^{-1}) and 16 wind directions (increments of 22.5°) were utilized. Frequencies of occurrence for each bin were calculated and plotted as histo-

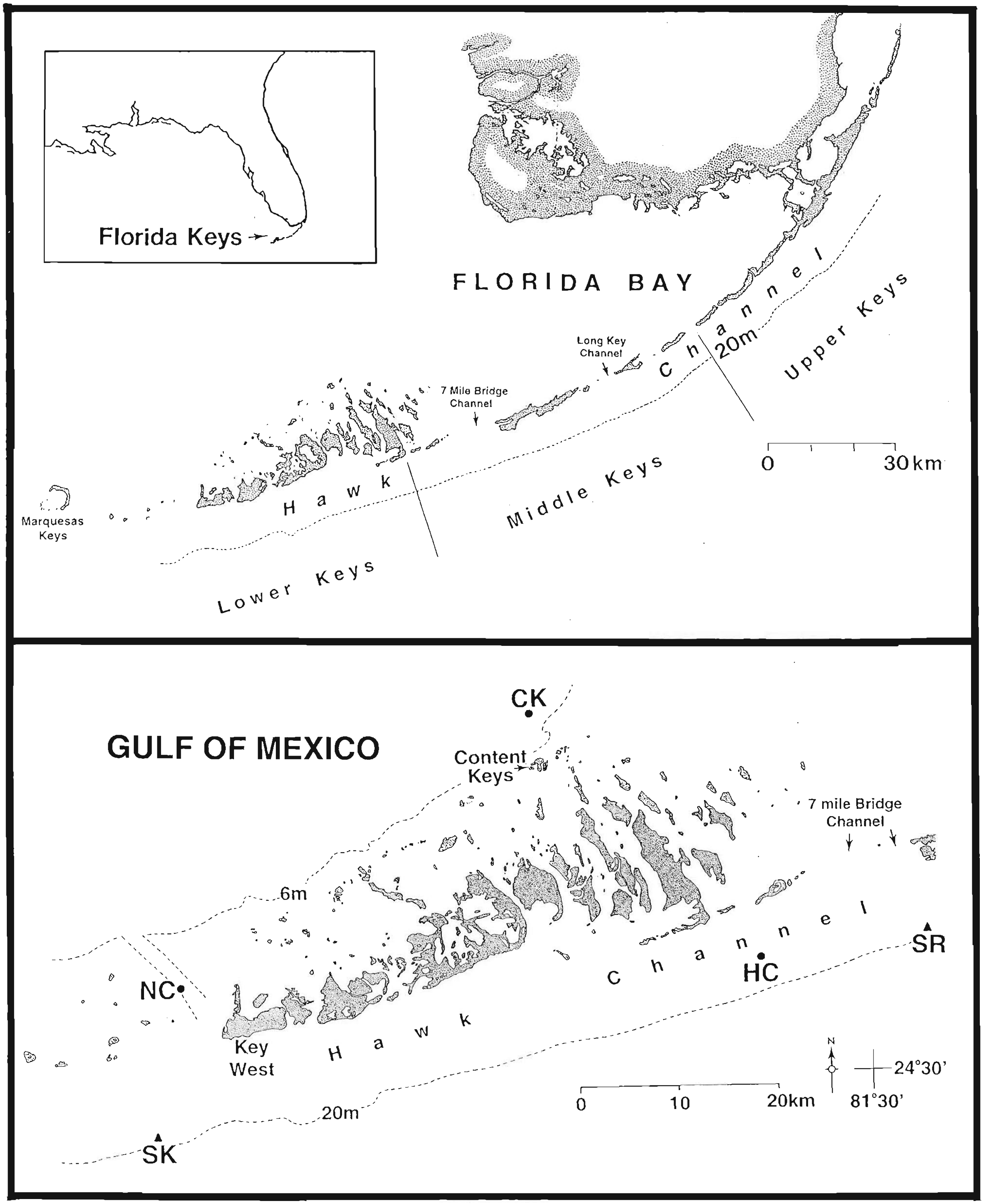

Figure 1. Map showing study sites in the Lower Keys. Dots labeled HC, NC and CK represent current meter sites in Hawk Channel, Northwest Channel and north of the Content Keys, respectively. Triangles labeled SR and SK represent C-MAN stations on Sombrero Reef and Sand Key, respectively. Parallel hatched lines west of Key West show the approximate lateral boundaries of Northwest Channel. The scale of the ancillary map is not sufficient to include the Dry Tortugas, which lie approximately 84 km due west of the Marquesas Keys.

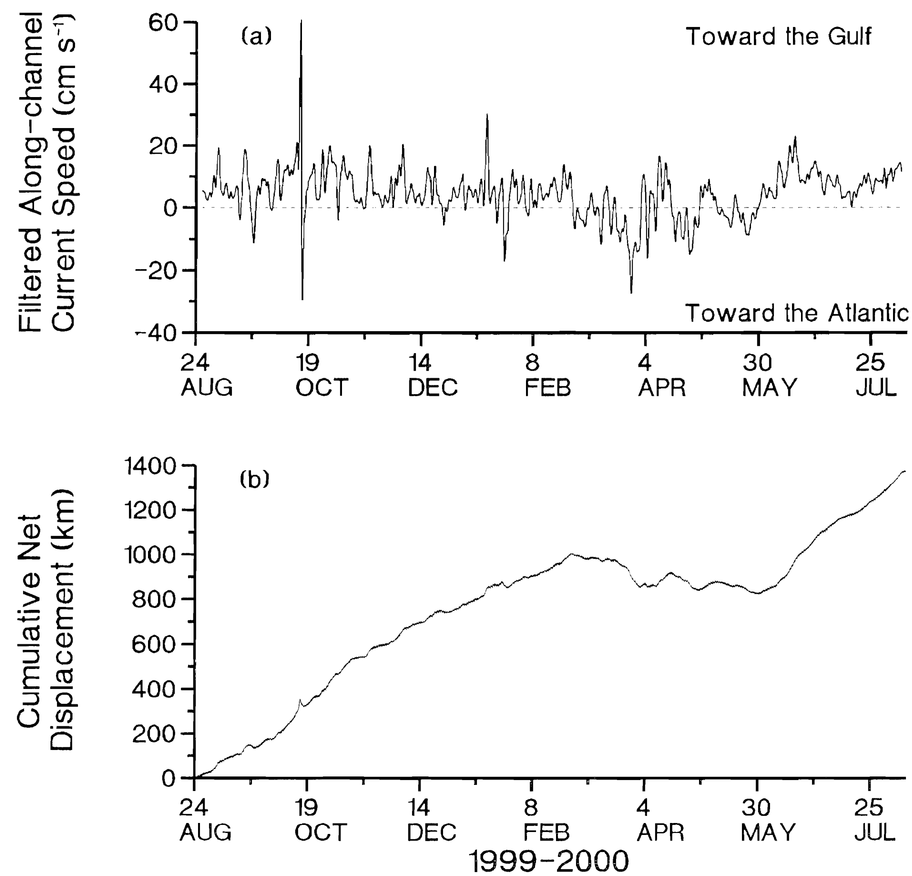

Figure 2. Low-pass filtered hourly along-channel current speed (a) and cumulative net displacement (b) through Northwest Channel, Aug. 24, 1999 to Aug. 11, 2000. Positive values in (a) and an ascending curve in (b) indicate flow into the Gulf of Mexico.

grams. Wind stress vectors were then calculated using the drag coefficient suggested by WU (1980) for moderate wind speeds (1–20 m s^{-1}). Air density was calculated as a function of pressure and temperature data. Spectral analysis (LITTLE and SHURE 1988) was used to investigate the relationship between wind stress and flow past the study sites. To determine the wind stress components and periodicities for which currents were most responsive, coherence spectra were calculated at 15° intervals of wind direction. Transfer function (gain) values quantified the variation in flow occurring in response to time-varying wind stress. To focus on the low-frequency response to wind forcing, both the flow and wind stress time series were low-pass filtered (BLOOMFIELD, 1976). Results are presented as contour plots of coherence and gain. Solid lines in the plots define regions of coherence significant above the 95% confidence limit (PANOFSKY and BRIER, 1963); dashed lines show contours of the gain.

RESULTS

Northwest Channel

Figure 2a shows that low-frequency along-channel currents in Northwest Channel generally ranged between −10 and +20 cm s^{-1} and currents typically fluctuated 5–15 cm s^{-1} over time scales of just a few days. A maximum nontidal inflow to the gulf of just over 60 cm s^{-1} occurred in mid October, which was followed immediately by a maximum nontidal outflow of −30 cm s^{-1}. Both were in response to the passage of Hurricane Irene through the lower Florida Keys. The standard deviation of low-frequency currents was 7.7 cm s^{-1}.

The plot of cumulative net displacement through Northwest Channel (Figure 2b) shows a long-term resultant flow into the gulf that averaged 4.5 cm s^{-1} over the 353-day study period. There was some indication of a seasonal signal as the net nontidal flow was toward the gulf from the beginning of the study period to late February and again from early June to the end of the study period. However, from early March to the end of May there was a resultant net outflow from the gulf that averaged 2.7 cm s^{-1}. During that time several reversals in outflow occurred that generally lasted about 2 weeks. Inflow to the gulf was comparatively steady during the last two months of the record. Tidal ebbs and floods, barely visible on the plot as very high-frequency fluctuations, dominate the instantaneous current through Northwest Channel, accounting for 93% of the total variance in observed along-channel currents. The M_2 constituent, the principal tidal constituent for this region, has an amplitude of 64 cm s^{-1}.

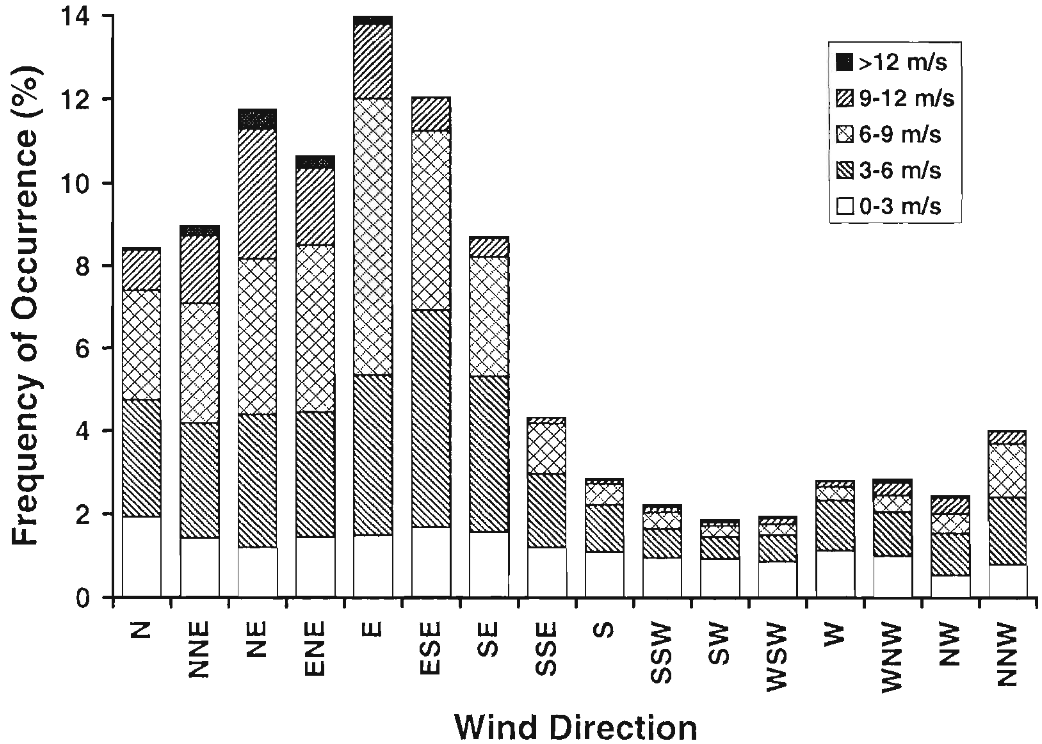

Figure 3. Histogram of wind directions and speeds recorded at Sand Key, Aug. 24, 1999 to Aug. 11, 2000. Each wind direction represents an arc of 22.5° and wind speeds have been subdivided into the 5 categories defined by the key.

The amplitudes of the other principal tidal constituents are 17 cm s^{-1} or less.

Winds at nearby Sand Key are predominately out of the eastern and northern quadrants during the nearly 1-yr study (Figure 3). Winds from the eastern quadrant account for 48% of the hourly readings while winds from the northern quadrant account for 29%. By comparison, winds out of the southern and western quadrants occurred only 14% and 9% of the time, respectively. Not apparent in the plot are the winds produced by Hurricane Irene on October 14–15 (see Fig. 2), whose eye passed almost directly over the weather station on Sand Key. Storm-induced winds reached 22.7 m s^{-1} from the east-northeast at Sand Key as the storm approached the study area from the south, which were followed within a few hours by winds from the west-northwest that reached 19.7 m s^{-1} as the storm moved northeast into Florida Bay.

Figure 4 shows the contour plot of coherence (at the 95% confidence limit) and gain (in cm s^{-1} per dyne cm^{-2}) for along-channel currents in Northwest Channel and wind stress recorded at Sand Key during the study period. Blank areas (*i.e.* areas without dashed lines) in the corners of the plot show regions of coherence below the 95% confidence limit. Negative gain values indicate flow toward the gulf (Atlantic) when winds are toward the western (eastern) quadrant. Most gain values are negative due to the convention assigned to flow direction and wind stress, *i.e.* negative gain values indicate that a positive wind stress produced a negative flow through the channel, or vice versa. For example, wind stress toward the east is defined as positive, and this wind direction produces a gulf-to-Atlantic (negative) flow through Northwest Channel, thus yielding a negative gain. The plot indicates that flow through Northwest Channel is significantly coherent with a broad range of wind stress components acting over time scales of 37–640 h (1.5–27 days, Fig. 4). Along-channel currents are most coherent with winds from the eastern and southeastern sectors. Highest coherence of 0.917—well above the 99.9% confidence limit—was observed for the 105–285° wind stress component at the 91-hr periodicity, indicating that this component of wind stress accounts for 92% of the variance in the along-channel flow through Northwest Channel over the 91-h periodicity. Gain values show that the E-W and ESE-WNW wind stress components are the most effective for forcing water through the channel. A maximum gain of −13.5 was obtained at the 91-h periodicity, indicating that a wind stress toward due west of 1 dyne cm^{-2} will force flow into the gulf that reaches nearly 14 cm s^{-1} at the 91-hr periodicity. Gain values ranged from −13.5 to +10.4 cm s^{-1} per dyne cm^{-2} at periodicities for which currents were significantly coherent with wind stress.

Gulf Shelf Site

Along-isobath currents at the shelf site north of the Content Keys dominated across-shelf components, accounting for nearly 73% of the total variance in nontidal flow past the current meter. Low-frequency along-shelf currents generally

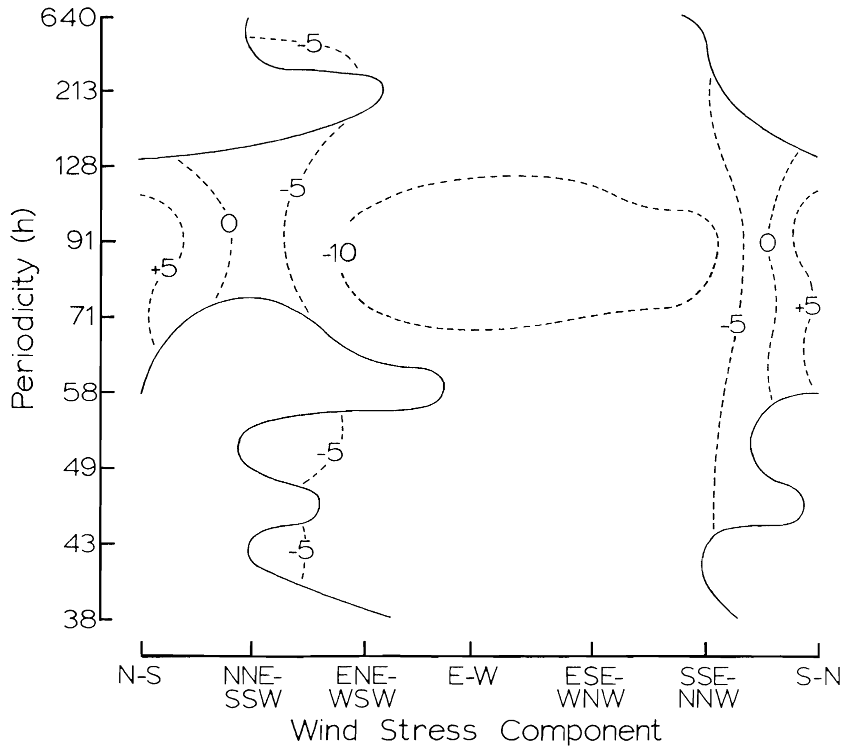

Figure 4. Contour plot of coherence at 95% confidence limit (coherence = 0.339, solid lines) and gain (in cm s^{-1} per dyne cm^{-2}, dashed lines) for along-channel currents in Northwest Channel and wind stress recorded at Sand Key, Aug. 24, 1999 to Aug. 11, 2000. Each tick mark on the x-axis is labeled with two compass points that are 180° apart signifying wind stress from either direction.

fluctuated between −3 and +2 cm s^{-1} with a standard deviation of 1.7 cm s^{-1} (Figure 5a). During the first and last thirds of the study period values are relatively evenly distributed between the positive and negative sides of the plot, resulting in little net movement. However, from mid October to early December along-shelf flow is toward the southwest, or toward Key West. The response to Hurricane Irene in mid October is readily apparent and begins with a strong along-isobath flow to the southwest reaching a maximum of nearly −8 cm s^{-1}, followed by strong flow to the northeast that reached a maximum of over 9 cm s^{-1}. Other significant southwestward flow events that occurred in late fall and early winter, were in response to cold fronts moving through the region. A plot of the cumulative net along-isobath displacement (Figure 5c) shows a slight resultant flow to the northeast during the first 5 weeks of the study period, followed by a 4-week time period of little net displacement. From late October to early December, net along-shelf flow past the study site is to the southwest, which is followed by a weak net flow in the opposite direction over the last 6 weeks of the study period. As a result of these low-frequency reversals, the resultant along-shelf flow for the 20-week study period is only −0.4 cm s^{-1} toward the southwest. Tidal co-oscillations are visible in the plot and harmonic analysis indicates that along-shelf tidal currents are relatively strong and account for nearly 90% of the total variance in along-shelf motions. The amplitude of the M_2 constituent is 15 cm s^{-1}, and amplitudes of the other principal tidal constituents are 5 cm s^{-1} or less.

The curve of low-pass filtered across-isobath currents falls on the positive side of the plot, indicating shoreward flow, through most of the 20-week study period (Figure 5b). Across-shelf currents generally ranged between −0.5 and +2 cm s^{-1} with a standard deviation of 0.8 cm s^{-1}. While the effects of Hurricane Irene are visible on the plot, they do not represent as great a perturbation in near-bottom across-shelf flow as occurred in the along-shelf flow. The cumulative across-shelf displacement (Figure 5c) shows a quasi-steady shoreward flow that averaged just over 1 cm s^{-1} during the study period. Across-shelf tidal motions are much weaker than along-shelf tidal motions, and account for only 15% of the total variance in across-shelf motions. The M_2 amplitude is only 1.4 cm s^{-1}. Tidal co-oscillations are not visible in the curve of across-shelf cumulative displacement.

The frequency of occurrence pattern for wind speeds and directions recorded at Sombrero Reef from Aug. 25, 1999 to Jan. 13, 2000 (not shown) is similar to the pattern described for Sand Key (Figure 3). Winds from the eastern and northern quadrants were most common, accounting for 43% and 37% of the total hourly observations during this nearly 5-mo period. Spectral analysis indicates significant coherence between along-shelf flow at the Content Keys study site and all wind stress components over time scales between 37–85 h

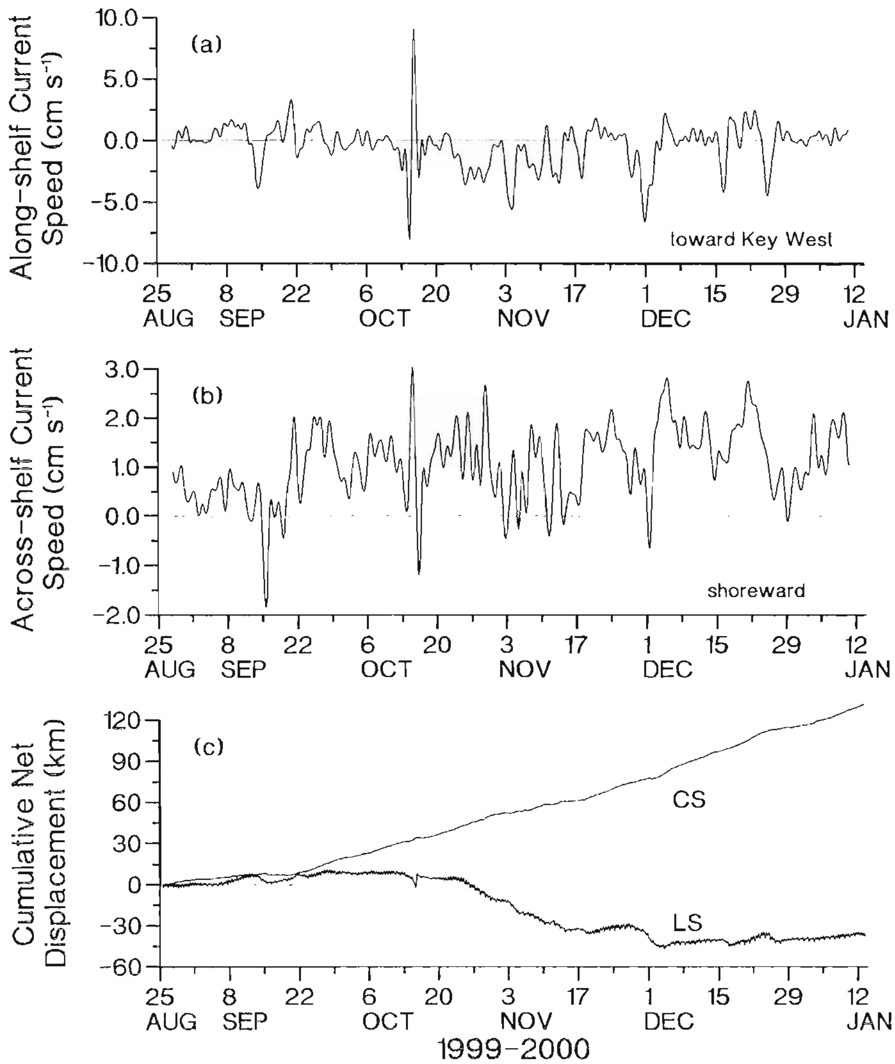

Figure 5. Low-pass filtered hourly along- (a) and across-isobath (b) currents, and cumulative along- and across-isobath displacement (c), past the study site north of the Content Keys, Aug. 25, 1999 to Jan. 13, 2000. Positive values indicate flow toward 060° in (a) and toward 150°, or shoreward, in (b). An ascending curve in (c) is toward 060° for along-shelf (LS) flow and toward 150° for across-shelf (CS) flow.

(Figure 6a). Highest coherence (0.91) occurred for the along-shelf wind stress component (ENE-WSW) at the 43-h periodicity. Transfer function values suggest that NNE-SSW winds are most effective for driving water in the along-shelf direction. The largest gain value (3.54 cm s^{-1} per dyne cm^{-2}) occurred for the NNE-SSW wind stress component at the 37-h periodicity. By comparison, while the SSE-NNW wind stress component is significantly coherent with along-shelf currents, the gain values indicate that this wind stress component is not especially effective in moving water along-shore past the study site.

Calculations also show statistically significant coherence between across-shelf flow and all wind stress components over time scales of 43–85 h (Figure 6b). Winds from the southeast quadrant are coherent with across-shelf currents over periodicities of 43–128 h (2–5 d). Highest coherence (0.653) occurred for the east-west wind stress component at the 51-h periodicity. The plot shows that all transfer function values for wind stress components between ENE-WSW and SSE-NNW are negative. By convention then, wind components from the east-northeast and the southeast quadrant coincide with shoreward-directed (toward the south-southeast) near-bottom currents. Winds from the opposite direction coincide with seaward-directed near-bottom currents. Gain values indicate that the SSE-NNW and ESE-WNW components are the most effective for driving across-shelf flow past the study site. A maximum gain of −0.67 cm s^{-1} per dyne cm^{-2} occurred at the 51-h periodicity for the SSE-NNW component. By comparison, NNE-SSW and ENE-WSW winds are the least effective for driving across-shelf flow at this site.

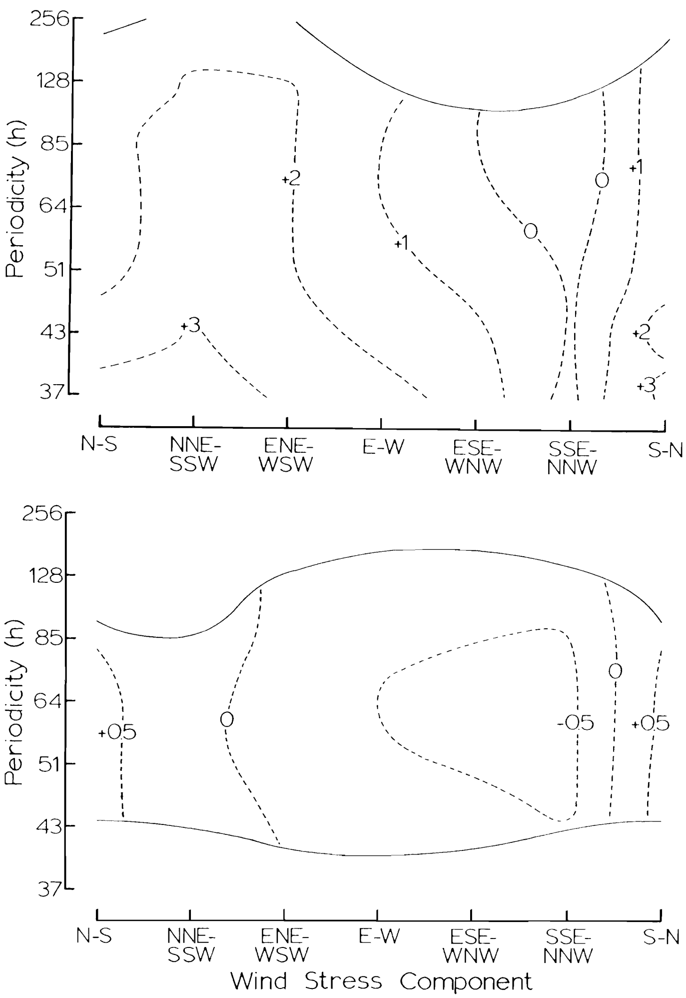

Figure 6. Same as Fig. 4 except for wind stress at Sombrero Reef and along-isobath (a) and across-isobath (b) currents recorded at the shelf site north of the Content Keys, August 25, 1999 to Jan. 13, 2000 (coherence = 0.343 at 95% confidence limit).

Hawk Channel

Figure 7 indicates that flow in Hawk Channel south of Bahia Honda Key is also dominated by along-shelf motion. Low-frequency along-shelf currents generally range between −15 and +10 cm s^{-1} with a standard deviation of 11 cm s^{-1} (Figure 7a). Values fall on the positive side of the plot nearly 70% of the time and account for the cumulative along-shelf displacement toward Key West that averaged 3.6 cm s^{-1} during this 13-month study (Figure 7c). A maximum nontidal current to the northeast of nearly +40 cm s^{-1} occurred in response to northward winds of up to 20 m s^{-1} (39 kts) associated with a strong late winter storm. After the storm front crossed the study area, winds shifted southeastward and quickly reversed the along-shelf flow. During this time nontidal flow to the southwest reached −47 cm s^{-1}. The plot exhibits no seasonal signal in along-shelf flow.

Low-frequency across-shelf currents generally range between −2 and + 7 cm s^{-1} with a standard deviation of 2.6 cm s^{-1} (Figure 7b). A maximum seaward nontidal flow of 15 cm s^{-1} was reached on December 10 in response to a cold front passing through the area. The response to the mid March storm appears as a temporary seaward flow that reached about 7 cm s^{-1} followed by a shoreward flow of less than 4 cm s^{-1}. The across-shelf perturbation due to the storm was of the same order of magnitude as much weaker meteorological forcing events. Values fall on the positive side of the plot 80% of the time indicating a seaward movement of water past the study site through most of the study period. The cumulative net across-shelf near-bottom flow was seaward at an average rate of 1.8 cm s^{-1}. There is an indication of a seasonal signal as currents were generally seaward from July to January and May to July, but little net across-shelf motion occurred from February through April.

Harmonic analysis indicates that tidal currents at the Hawk Channel site are relatively weak. The along and across-shelf M_2 amplitudes are only 2.8 and 2.7 cm s^{-1}, respectively. All other diurnal and semi-diurnal constituents have amplitudes of less than 1 cm s^{-1} and, thus, fall within the precision of the current meter used to make the measurements. Tidal components account for approximately 15% and 21% of the total variance in along- and across-shelf current motions, respectively.

A vector plot of currents recorded 10 m above the bottom in Hawk Channel from April 14 to May 25, 1993 (not shown), indicates a flow pattern that is very similar to that recorded 4 m above the bottom during the same time period. The resultant current vector at the upper level was 7.2 cm s^{-1} with a heading of 246° while near-bottom current vectors had a resultant speed and direction of 5.8 cm s^{-1} and 240°, respectively. The linear regression correlation coefficient of the along- and across-shelf currents at the two levels was +0.906 and +0.472, respectively, both values significant well above the 99.9% confidence limit. The complex correlation coefficient (KUNDU, 1976) for the combined along- and across-isobath components at the upper and lower levels was 0.877 (highly significant), and on average the current direction at the lower level was 9.6° to the left of the current direction at the upper level. These results indicate that currents at the two levels at the study site were moving in unison, at least during the 6-wk overlap period in mid spring.

The histogram of wind direction/speeds recorded at Sombrero Reef from July 2, 1992 to July 22, 1993 (Figure 8) shows a slightly different pattern than the plot constructed from winds recorded at Sand Key in 1999–2000. The Sombrero Reef winds were predominately out of the eastern quadrant, accounting for nearly 70% of the hourly observations during the 1-yr study. Winds from the northern sector are less common than those described above for Sand Key (1999–2000). However, the mostly westward winds have a significantly greater southward component during winter months (not shown). Like the record from Sand Key, winds out of the western quadrant are relatively rare, accounting for less than 10% of the hourly observations. The annual pattern is highly similar to other wind records from Sombrero Reef (PITTS and SMITH, 1997).

Results of spectral analyses indicate that along-isobath flow in Hawk Channel is significantly coherent with virtually

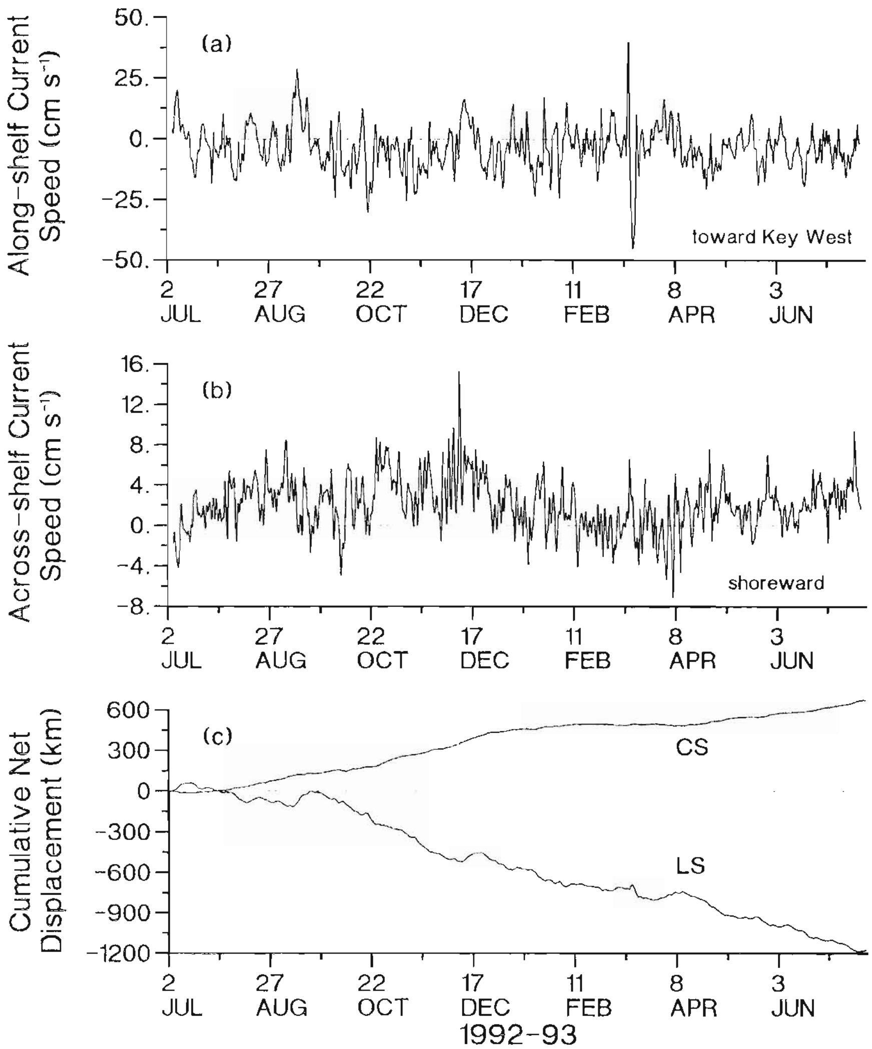

Figure 7. Low-pass filtered hourly along- (a) and across-shelf (b) currents, and cumulative along- and across-shelf displacement (c), past the study site in Hawk Channel from July 2, 1992 to July 22, 1993. Positive values indicate flow toward 075° in (a) and toward 165°, or seaward in (b). An ascending curve in (c) is toward 075 for along-shelf (LS) currents and toward 165° in across-shelf (CS) flow.

all wind stress components at periodicities of 38–40 h, 53–58 h and 80–160 h (Figure 9). Coherence and gain values indicate that along-shelf currents were most closely coupled with E-W and ENE-WSW wind stress components. Coherence was significant above the 95% confidence level for all time scales greater than 49 h for along-isobath currents and these wind stress components. Highest coherence (0.817) was found for the ENE-WSW wind stress at the 107-h (4.5-day) periodicity. Phase spectra indicate that the time lead of the ENE-WSW component of wind stress over along-shelf flow was approximately 6 h. The transfer function value using this wind stress component and periodicity is +8.0 cm s^{-1} per dyne cm^{-2}. The highest gain calculated (+11.8 cm s^{-1} per dyne cm^{-2}) occurred for the NE-SW component at the 160-h periodicity. Gain values ranged between −4.6 and +11.8 cm s^{-1} per dyne cm^{-2} for periodicities at which wind stress was significantly coherent with along-shelf flow. Spectral analyses indicate no statistically significant coherence between across-shelf flow in Hawk Channel and any component of wind stress.

DISCUSSION

The long-term flow observed through Northwest Channel is inconsistent in at least two ways with the long-term flow reported through tidal channels in the Middle and Lower Keys (Smith, 1994, 1998, in review). First, and probably most importantly, the earlier studies showed a quasi-steady outflow from Florida Bay or the gulf and into the Atlantic through all major tidal channels. Long-term flow through Northwest Channel is in the opposite direction in the present study. Second, all earlier records showed temporary reversals in long-term flow that occur throughout the year, but which lasted only on the order of several days to about a week. Reported seasonal signals are minimal and are described as

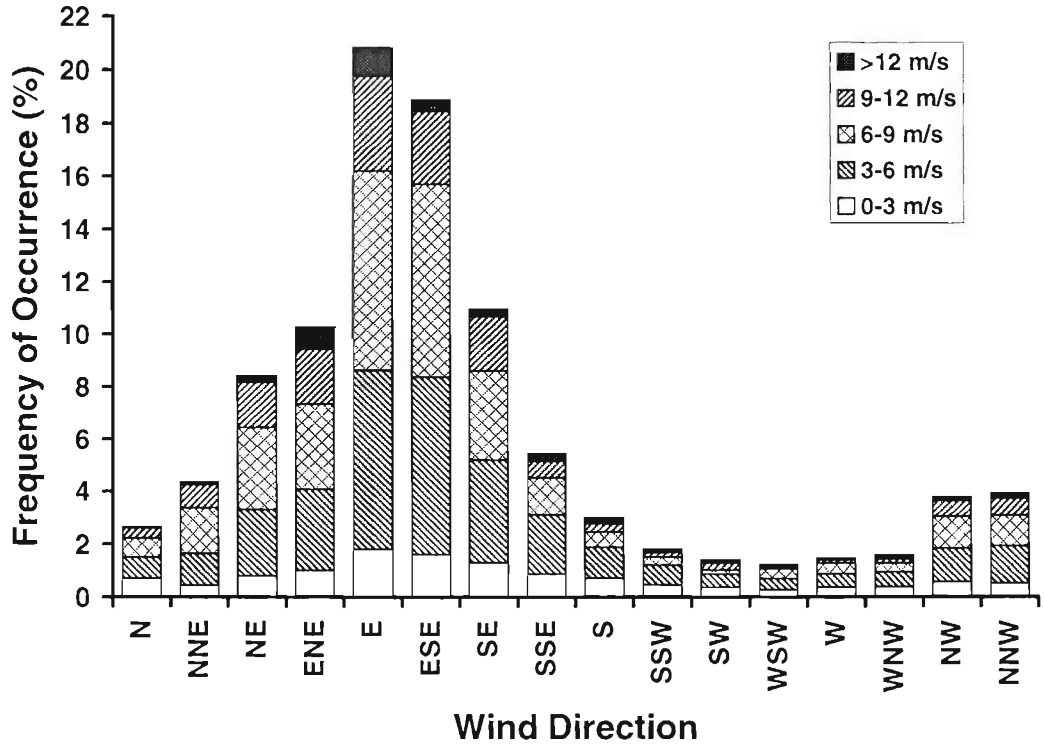

Figure 8. Same as Fig. 3 except for Sombrero Reef, July 2, 1992 to July 22, 1993.

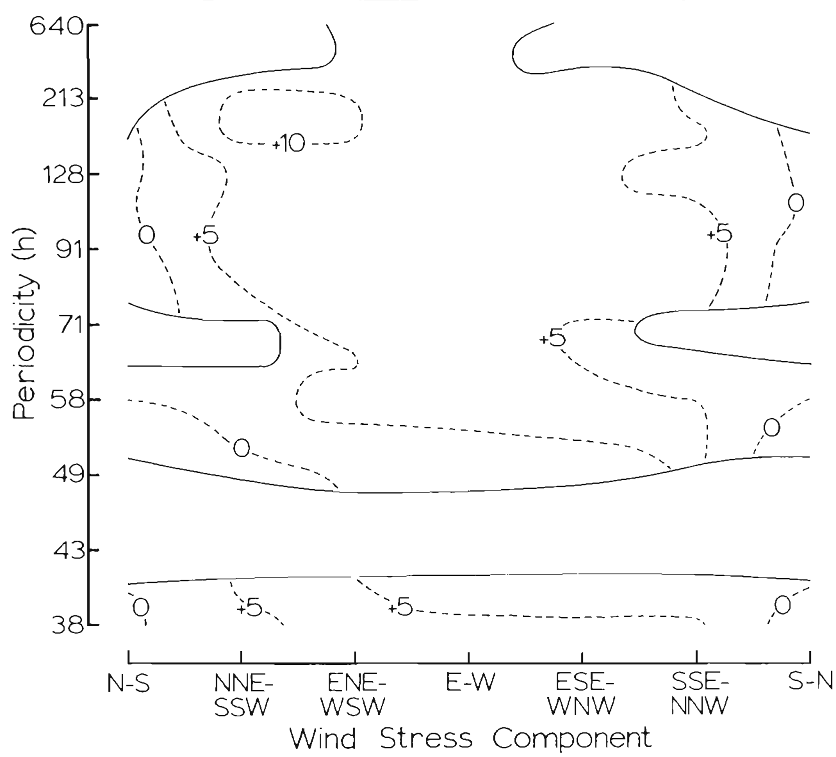

Figure 9. Same as Fig. 4 except for wind stress at Sombrero Reef and along-isobath currents recorded in Hawk Channel, Jul. 2, 1992 to Jul. 22, 1993 (coherence = 0.324 at 95% confidence limit).

subtle variations in outflow rates. By comparison, in the present study inflow observed through Northwest Channel was interrupted by a 3-month reversal that occurred from late February and lasted through early June.

It is unclear why the long-term flow through Northwest Channel is contrary to the long-term patterns observed in other channels in the Middle and Lower Keys. SMITH (in review) has shown that low-frequency flow through Long Key and Seven-Mile Bridge channels is coherent with the local wind field, particularly the southeast-to-northwest wind stress component. However, the long-term gulf-to-Atlantic flow through these channels is generally upwind, especially during spring and summer months. So, while wind forcing can be shown to explain a large percentage of the low-frequency variation about the resultant flow through these two channels, the forcing that produces the resultant flow is more complex. In other studies, SMITH (2000) and WANG *et al.* (1994) have documented a tide-induced set-up in Florida Bay that may drive the observed long-term outflow. Alternatively, HETLAND *et al.* (1999) have reported sea level height differences of 10–30 cm between the southwest Florida shelf and shelf waters on the Atlantic side of the Keys. A study by LEE and SMITH (in review) suggests that this sea level difference is responsible for the long-term outflow observed through Long Key Channel. Results presented here indicate that the westward (prevailing) and northwestward wind stress components are likely driving both the low-frequency and long-term flow into the gulf through Northwest Channel. During the 3-mo reversal in late winter and early spring, winds were also predominately from the prevailing eastern sector—conditions favorable for Atlantic-to-gulf flow. Also, wind strength during that time was typical for the season—somewhat weaker than during fall and winter months but stronger than during the prolonged summer season. So, if the tidal processes and sea level differences noted above had overridden the wind stress response to produce the March–May reversal observed in Northwest Channel, one would expect the reversal to have extended into the summer months when winds were even weaker and more variable. However, the data clearly show an Atlantic-to-gulf flow during the summer season.

While the Northwest Channel flow pattern generally contradicts patterns observed in other Keys channels, the current pattern observed at the shelf site in Hawk Channel is similar in several respects to the one documented by PITTS (1994) at the same site during the late summer and fall months of 1991. First, both studies showed that currents in this region of Hawk Channel are dominated by along-shelf motions, with a resultant displacement toward Key West. Second, while the along-shelf currents are significantly coherent with a broad range of wind stress components, they are most closely coupled with the along-shelf orientation of wind. The earlier study showed coherence between these two variables at the 3–4 d periodicities, while the longer time series reported here showed a significant cause-and-effect relationship over all time scales between 2–27 d. Third, across-shelf currents, although weaker than along-shelf currents, are significant and the net flow was directed seaward during both study periods.

The most notable difference in results between the two Hawk Channel studies is the apparent lack of any cause-and-effect relationship between across-shelf currents and wind stress in the data presented here. The earlier study (PITTS, 1994) showed significant coherence between across-shelf currents and along-shelf wind stress at the 2–3.5 d periodicities, with a phase relationship suggesting a near-bottom return flow of shoreward-directed Ekman transport. A follow-up study from a Hawk Channel site off Key West (PITTS, 1997) showed that the relationship between winds and across-shelf currents was inconsistent. For part of the study period the variables appeared to alternate between an in-phase and out-of-phase relationship. During another time period, across-shelf currents and across-shelf wind stress exhibited an out-of-phase relationship, suggesting an upwind return flow of near-bottom currents. By comparison, the data presented here show no statistically significant coherence between near-bottom across-shelf currents and any component of wind stress. Also, the high degree of similarity between current motions at the upper and lower levels at the Hawk Channel study site suggests that the water column is moving as a whole, *i.e.* there is no indication of current shear that would be consistent with the idea of a near-surface shoreward-directed transport and a near-bottom return flow.

By comparison, spectral analysis revealed a close coupling between near-bottom across-shelf flow north of the Content Keys and wind stress. Transfer function values indicate an inverse relationship between across-shelf currents and winds from the southeast quadrant. For example, a north-northwestward (negative) wind stress acting over the 51-h periodicity will drive a shoreward (positive) across-shelf near-bottom current of roughly 0.7 cm s^{-1} past the study site. This suggests that seaward (shoreward) winds are driving near-surface waters seaward (shoreward) and setting down (up) coastal waters levels. In turn, the observed near-bottom currents are responding as an upwind return flow to these wind-forced pressure gradients. Phase spectra (not shown) reveal an approximately 180° shift between across-shelf currents and across-shelf wind stress, which supports the concept of an upwind return flow. The prevailing westward winds will, therefore, drive an onshore near-bottom current, which probably accounts for the observed resultant shoreward displacement. The wind analysis also suggests that Ekman dynamics may be playing a role in the across-shelf flow. Along-shelf wind stress is significantly and inversely related to across-shelf flow, indicating a near-bottom shoreward return flow of Ekman-driven seaward near-surface flow.

CONCLUSIONS

Combining the long-term flow patterns described in this study with the earlier tidal channel (SMITH, 1994, in review) and Hawk Channel results (LAPOINTE *et al.*,1992; PITTS, 1994), suggests a clockwise circulation of near-shore waters in this region, at least for part of the year. The 3-mo reversal in Atlantic-to-gulf flow through Northwest Channel during late winter and spring may represent a seasonal shift, which would periodically disrupt the loop circulation, or it may represent an occasional, but unpredictable, perturbation in the loop flow. While the resultant along-shelf displacement over the shelf north of the Content Keys was toward Key West, which is contrary to the clockwise loop concept, most of the southwestward flow occurred during a relatively brief 6-week period from late October to early December. For much of the remainder of the study period along-shelf displacement was minimal, but generally northeastward. Also, the long-term shoreward near-bottom flow north of the Content Keys will feed into tidal channels that connect gulf and Atlantic waters in the Middle and Lower Keys.

The clockwise near-shore circulation pattern is consistent with, and likely part of, a larger clockwise circulation loop described by LEE and WILLIAMS (1999) as the "western Florida Bay/coastal counter current route." Using moored current meters, drifter data (LEE *et al.*, 1994; LEE *et al.*, 1996), and incorporating SMITH's (1994) tidal channel results, they were able to document a clockwise loop that begins with southeastward flow from the southwest Florida shelf through western Florida Bay and into shelf waters on the Atlantic side of the Middle or Lower Keys. As water flows out onto the shelf it becomes entrained in the wind-driven coastal counter current and is transported to the Marquesas Keys or Dry Tortugas. From there it may turn back northeast toward the Florida Peninsula.

LEE and WILLIAMS (1999) note that the western Florida Bay/coastal counter current route may play an important role as a larval retention mechanism for pelagic larvae spawned in the Florida Keys coastal waters, especially near the reef tract. They estimate that the larger-scale loop they have observed may retain larvae for up to 2–3 months. The smaller-scale sub-loop described here would likely retain larvae over shorter time scales—on the order of weeks. Results from these types of studies should allow larval ecologists to better track the movement of larvae from an important source—the Florida reef tract—to the region's primary nursery grounds—Florida Bay. This is just one example of how an understanding of coastal circulation features such as this may play an important role in how the resources of this sensitive region are managed and utilized.

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