Net Transport Through Three Tidal Channels in Northern and Northeastern Florida Bay

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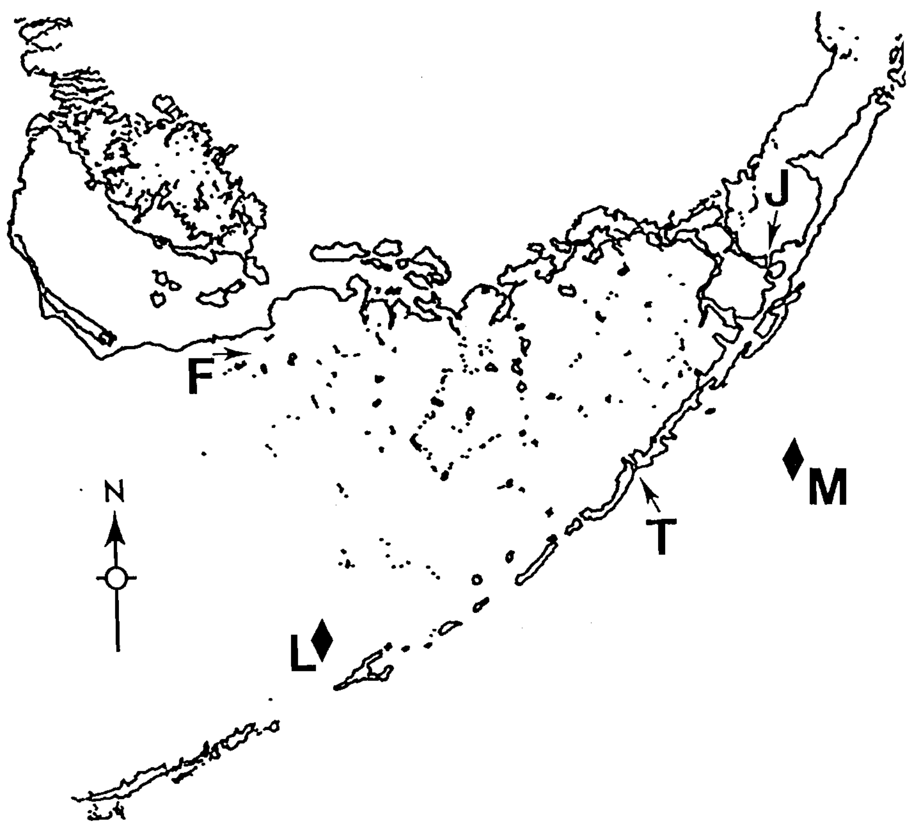

Figure 1. Map of Florida Bay showing locations of study sites in Jewfish Creek (**J**), Tavernier Creek (**T**) and in the main channel just south of Flamingo. Diamonds labelled **M** and **L** represent the locations of C-MAN stations on Molasses Reef and north of Long Key, respectively.

INTRODUCTION

The circulation within and in waters surrounding Florida Bay is a complex response to forcing by tides, winds and freshwater outflow from the Everglades. Tidal processes are complicated by the interaction of distinctly different tidal waves moving through the bay from the Gulf of Mexico and Atlantic Ocean. Both wind forcing and freshwater entering the system vary significantly over time scales ranging from hours to seasons. Further complicating circulation is the bay's bottom topography, which is characterized as a mosaic of mud banks, seagrass beds, mangrove islands and shallow sub-basins or "lakes."

Until recently, little information on the bay's flow patterns had been obtained through direct measurement. Field observations are required for understanding the transport processes and pathways taken by dissolved and suspended material moving into, through and out of Florida Bay. They are also critical for determining the exchanges that occur between the bay and the Gulf of Mexico to the west and Atlantic Ocean to the east and south . These exchanges help maintain or re-establish water quality by providing a flushing action.

This report describes the results of a 16-month circulation study conducted in the northern and northeastern parts of Florida Bay between September, 1995 and December, 1996. The study represents the third phase of a multi-year investigation of physical processes in Florida Bay. Phase one (Smith and Pitts 1994, 1995) focused upon tidal and nontidal fluctuations in water level, using the data base assembled through the Marine Monitoring Network. Phase two (Pitts and Smith 1995) focused on currents in three major tidal channels connecting sub-basins in the northwest part of Florida Bay. The purpose of this third phase of the study is to quantify the movement of water entering the northern and northeastern region of Florida Bay from the Gulf of Mexico to the west and from Barnes Sound and Hawk Channel to the east, and thereby contribute to an understanding of regional flow patterns. The study represents an expansion of the earlier circulation work in a geographical sense, but it is similar to previous work in the sense that the objectives are to characterize tidal and nontidal components of the flow, to establish long-term net flow patterns, and to quantify volume transport. Results will also be useful for verifying computer simulations of Florida Bay circulation.

THE DATA

The data used in this report were collected hourly from three channels in the northern and northeastern parts of Florida Bay. One of the study sites was located 2 km south of Flamingo (25° 07.12′ N, 80° 55.72′ W) in the main channel connecting the interior of Florida Bay with the open waters of the Gulf of Mexico to the west. Current meter data were recorded from September 14, 1995 to January 30, 1996. Data collection from the two sites in the northeastern section of the bay were delayed somewhat from the starting time specified in the contract because the Park Service current meters were left in operation in Conchie Channel, Iron Pipe Channel and Man of War Channel to obtain a full year's record at those locations. Current meters began recording data at study sites in

Jewfish Creek (25° 11.19′ N, 80° 23.28′ W) and Tavernier Creek (25° 00.32′ N, 80° 31.57′ W) on October 25, 1995. The Tavernier Creek record ends on December 9, 1996, while the Jewfish Creek time series continues to December 12, 1996.

The General Oceanics Mark-II current meters used in this study record current speed and direction as well as water temperature. Some of the current meters are fitted with conductivity sensors, thereby providing information on salinity. Current speeds and directions are accurate to ±1 cm s^{-1} and ±2°, respectively, according to instrument specifications. Conductivity readings are accurate to ±2.5 mS cm^{-1}, although the resolution of the sensor is ±0.1 mS cm^{-1}. Temperatures recorded by the current meter have an accuracy of ±0.25° and a resolution of 0.02°.

In addition to the current meter data, we have bottom pressure data from each channel for abbreviated time periods to support our calculations of volume transport. Data were recorded with Brancker Model TG-205 pressure recorders which have an accuracy of 0.05 db over a total pressure range of 0-20 decibars (db) (0-30 psia). Bottom pressures were recorded at the Flamingo study site from September 14 to December 6, 1995; in Jewfish Creek from June 18 to December 11, 1996; and in Tavernier Creek from December 7, 1995 to July 30, 1996.

Wind data recorded at C-MAN meteorological stations on Molasses Reef (25° 00.60′ N, 80° 22.80′ W) and 10 km northwest of Long Key (24° 37.60′ N, 80° 06.60′ W) were obtained from the National Data Buoy Center to investigate the relationship between flow through the channels and local wind stress. The C-MAN wind speeds and directions are recorded to the nearest 0.01 m s^{-1} and 1°, respectively.

METHODOLOGY

Because flow at all three study sites was confined by a channel, current vectors (speed and direction) were decomposed into along-channel and across-channel components and only the along-channel components were retained for analysis. The along-channel component was defined to be the direction at which the mean across-channel flow was zero. The along-channel heading was determined independently for both flooding and ebbing currents.

At all three study sites, tidal fluctuations in the current tend to obscure the more subtle, low-frequency variations that occur in response to wind forcing and freshwater outflow. To emphasize the long-term net movement of water past the study site at the expense of the tidal fluctuations, we present current meter data as cumulative net displacement and cumulative net volume transport plots. Displacement is defined to be the product of the current speed and the one-hour time period that it represents. At our Flamingo study site, positive currents, and therefore positive displacement and volume transport, indicate westward flow (260°) toward the Gulf of Mexico. At the Jewfish Creek study site, positive currents indicate southward flow (191°) into Blackwater Sound. At the Tavernier Creek study site, positive currents indicate west-northwestward flow (287°) into Florida Bay.

An alternate way to emphasize nontidal fluctuations in along-channel current, but without accumulating the displacement of water past the current meter, involves low-pass filtering the hourly along-channel current components. We use the 127-weight Lanczos filter described by Bloomfield (1976) to remove semidiurnal and diurnal tidal period fluctuations from our longer time series. This filter has a half-power point at a period of 37 hours, and 63 hours of data are lost at each end of the time series.

Volume transport calculation methodology varied according to the nature and size of the channel under investigation. Tavernier Creek, for example, has a width of 68 m and is bounded by solid banks, while Jewfish Creek is only 36 m wide and it is bounded by mangroves growing in shallow water. At the Flamingo study site, the channel has a width of 525 m and is unbounded, although it is clearly defined by shallow water on both sides.

Volume transport calculations require an estimation of the vertically and laterally integrated along-channel current speed. In all cases we integrate vertically by assuming that the surface-to-bottom current profile is logarithmic:

$$u(z) = \frac{u_*}{k} \ln\frac{z}{z_o}, \tag{1}$$

where u(z) is the *in situ* current speed, u_* is the friction velocity, k is the von Kármán constant (0.41), z is the height above the bottom at which the current speed is measured and z_o is the roughness length. Measurements provide the *in situ* currents needed to estimate the friction velocity. Using the total water depth, equation (1) can be used to estimate the surface current speed at the study site, u(0). The mean water column current speed is then given by

$$U = \frac{u_*}{k\Delta z} \left(Z \ln\frac{Z}{z_o} - \Delta z\right), \tag{2}$$

where Δz is the difference between the spatially averaged segment depth, Z, and the roughness length.

In the relatively protected waters of Tavernier Creek and Jewfish Creek, it is reasonable to assume that wind forcing is minimal. In the east-west channel south of Flamingo, on the other hand, it is possible that wind forcing can produce significant changes in the speed and direction of the current in surface layers. At all stations, it is possible that along-channel density gradients can influence the lower part of the water column, but it was beyond the scope of the study to obtain the hydrographic data needed to quantify baroclinic forcing.

The lateral variation in along-channel current speed was investigated by obtaining *in situ* surface current measurements at three or more stations, including one in the center of the channel. Volume transport for a given hour was obtained by summing the contributions from the segment represented by each of the stations: the product of the mean segment depth and the cross-sectionally averaged current speed. The mean segment depth was obtained from closely-spaced depth measurements.

The cross-sectionally averaged current speed was obtained in either of two ways, depending upon the width of the channel. For the two narrow channels with regular bottom topography (Jewfish Creek and Tavernier Creek), the lateral variation in along-channel current speed was assumed to be parabolic and of the form

$$u(y) = u(0)\ (1-n)\ (\frac{y}{\Delta y})^2, \tag{3}$$

where u(0) and u(y) are the surface current speed in mid channel and at distance y from the center of the channel, respectively; n is the current speed at the edge of the channel, expressed as a fraction of the mid-channel current speed; y is the distance from the center of the channel and Δy is half the total width of the channel. Values for n were obtained for both flood and ebb conditions to account for flood-dominant and ebb-dominant parts of the channel. The mean surface current speed for the jth segment in a narrow channel was found by integrating equation 3 laterally from the center of the channel to either bank:

$$U_j = \frac{1}{\Delta y} \int_0^{\Delta y} u(y)\,dy. \tag{4}$$

The volume transport for a given hour is then obtained by multiplying the mean segment depth by the mean current speed and summing the contributions of the m segments:

$$T_j = \sum_{j=1}^{m} U_j\, Z_j, \tag{5}$$

where Z_j is the mean depth of the jth segment.

For the wider channel south of Flamingo we established four anchor stations to define lateral variations in current speed. Hour-by-hour volume transport was obtained from equation (3), using the assumption that the surface current obtained by drogue or flow meter measurements represented the entire segment. Also, calculations assumed that the relationship between u(y) and u(0), i.e., n, remained constant throughout the flood or ebb tide cycle.

Harmonic constants of the principal tidal constituents for the along-channel currents were quantified using two methods depending on the length of the time series. For records shorter than six months in length, which includes the current meter and pressure data from Flamingo and pressure data from Jewfish Creek, a 29-day harmonic analysis computer program was used (Dennis and Long, 1971). The program calculates the amplitude and phase angle of 24 tidal constituents. Since these time series were substantially longer than 29 days, we conducted several analyses and then vector averaged the harmonic constants.

For time series longer than six months harmonic constants were quantified using the NOS least squares harmonic analysis program, "LSQHA" (Schureman, 1958). Harmonic analyses were also used on each volume transport time series to provide the amplitudes needed to quantify the amount of water moving through the channels over each half tidal cycle. The total volume of water carried through the channel between consecutive slack tides is given by

$$T_V = \frac{AP}{\pi} \qquad (6)$$

where A and P are the amplitude and period of the tidal constituent, respectively.

To investigate the effect of local wind stress on along-channel flow, wind speeds and directions were first converted to wind stress vectors using the method described by Wu (1980). To determine the wind stress component to which along-channel volume transport was most responsive, a series of wind stress components were paired with volume transport through a given channel. The optimum wind stress component, identified by the highest correlation coefficient, was then used for a spectral analysis (Little and Shure, 1988). Coherence spectra show whether there is significant coupling between winds and currents and over what time scales. Phase spectra indicate the time lag between wind stress forcing and the responding currents, while energy density and transfer function spectra provide the information needed to quantify the change in current speed that occurs in response to a change in wind forcing. Results of the analyses are not shown graphically in this report, although we describe our findings in the Results section.

Conductivity has been converted to salinity using the practical salinity scale (Perkin and Lewis, 1980). In accordance with Millero (1993), we do not use the term "parts per thousand" or the abbreviation "‰." Water samples taken alongside a "clean" conductivity sensor in water of various salinities were used to calibrate the sensor. In this way we can use the instrument's resolution of 0.1 mS cm^{-1}, rather than the accuracy inherent in the current meter, for reporting results of our salinity calculations. Over the range of temperatures and conductivities recorded during the study period a conservative accuracy value of ±0.2 was calculated. A water sample taken alongside the conductivity sensor at the end of the deployment was used to determine the effect of biological fouling on sensor readings. Effects of fouling were assumed to increase linearly over time and adjustments to the salinity time series were made accordingly. Salinity and temperature data are presented as time series plots.

RESULTS

Most of the results of this third study are presented in "executive summary" form. Plots of the time series are accompanied by expanded captions that are short enough to fit onto a single page. Captions describe where and when the time series was recorded, provide an overview of the plot and call attention to plots of directly related results. The final part of the results section describes the spectral analysis of wind stress and along-channel transport through the three channels.

Figure CND96JFC. Cumulative net displacement of the along-channel current components in Jewfish Creek, a tidal channel connecting Blackwater Sound (northeast Florida Bay) with Barnes Sound (see **Figure 1** for station location). Data were recorded hourly 1 m above the bottom in 3.5 m of water from October 25, 1995 to December 12, 1996. Positive displacements indicate a flow of water from Card Sound into Florida Bay.

The plot is dominated by low-frequency reversals which occur repeatedly throughout this 414-day time series. These low-frequency fluctuations occur over time scales of several days to about two weeks. For approximately the first 7 months of the study period the reversals result in negligible net displacement. However, from mid June to the end of September there is a net flow out of Blackwater Sound that averaged 9.2 cm s^{-1}. Over the last two and a half months of the study the net transport reverses and water flows into Blackwater Sound at an average rate of 17.2 cm s^{-1}. A comparison of local wind data and along-channel flow indicates that wind stress is largely responsible for the low-frequency variability observed in the along-channel flow (see the end of the Results section of this report for details of the wind analysis).

Although they are impossible to see in this very long time series tidal ebbs and floods often dominate the instantaneous current. Harmonic analysis indicates that the amplitude of the M_2 tidal constituent at the study site is nearly 23 cm s^{-1}. See **Table 1** for a list of amplitudes and phase angles for the principal tidal constituents.

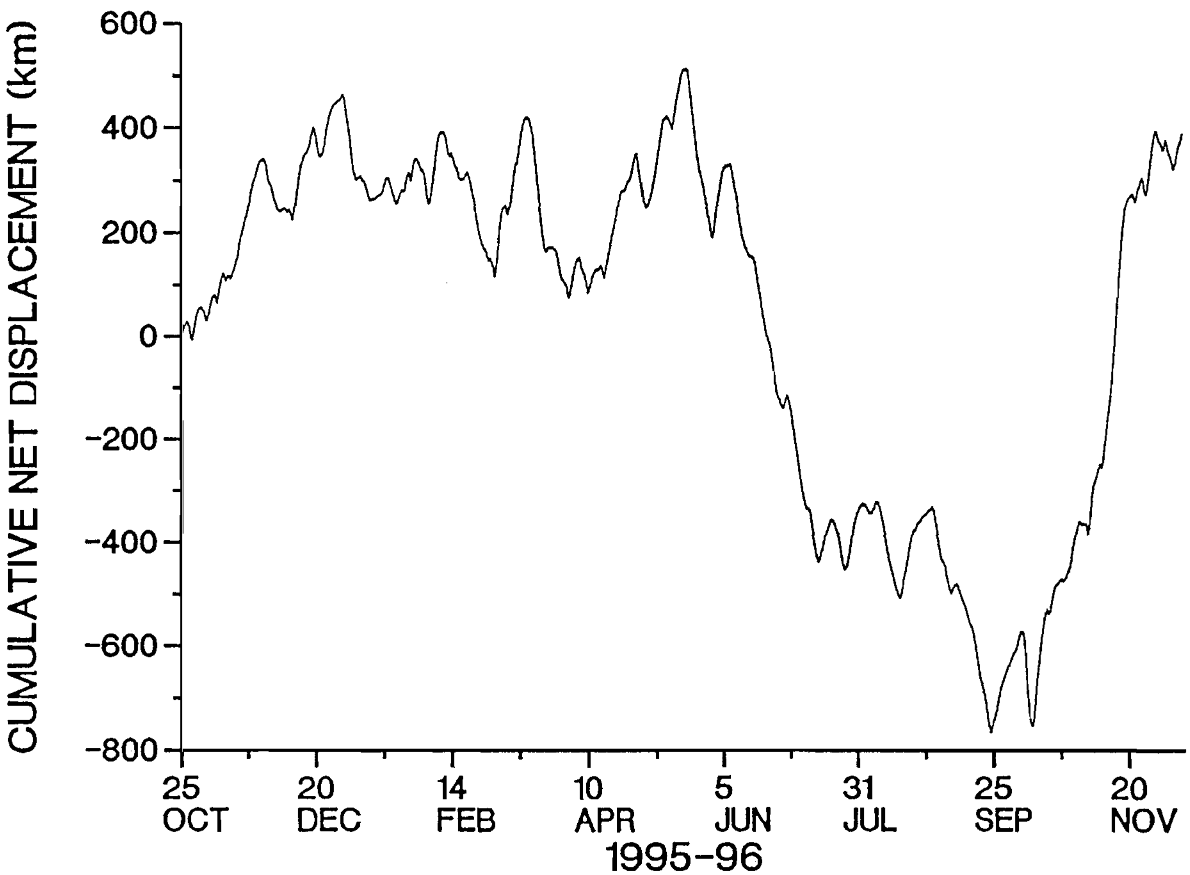

Figure NC96JFC. Nontidal, along-channel current components from Jewfish Creek (see **Figure 1** for station location). Currents were recorded near mid-channel 1 m above the bottom in 3.5 m of water from October 25, 1995 to December 12, 1996. Current speeds and directions were decomposed into along-channel and across-channel components, then the along-channel components were smoothed with a numerical filter to remove the ebb and flood of the tide. Positive values indicate flow toward 191°, or into Blackwater Sound.

The pattern shows large fluctuations in the along-channel, nontidal currents throughout this 414-day study period. Current speeds commonly fluctuate 30-60 cm s^{-1} over time scales of only a few days. A maximum nontidal outflow from Blackwater Sound of 100 cm s^{-1} was recorded in early October which was immediately followed by an inflow of over 70cm s^{-1}. The standard deviation of the filtered along-channel components is 26.5 cm s^{-1}. Further analysis indicates that the nontidal currents account for nearly 80% of the total variance in the along-channel flow.

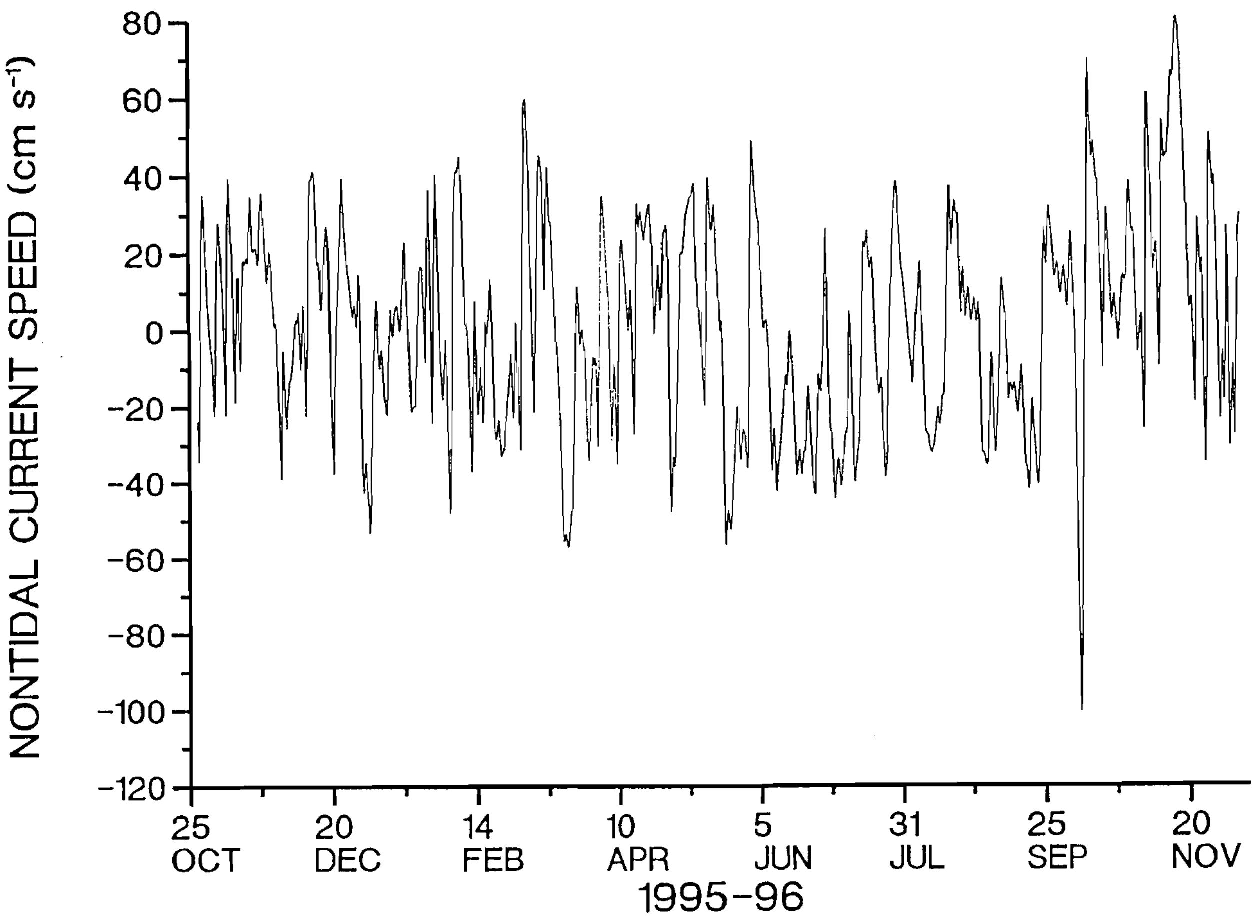

Figure CVT96JFC. Cumulative volume transport through Jewfish Creek from October 25, 1995 to December 12, 1996 (see **Figure 1** for station location). An ascending curve indicates a southward flow through Jewfish Creek from Barnes Sound into Blackwater Sound.

Volume transport through Jewfish Creek is characterized by low-frequency reversals which occur repeatedly throughout this 414-day time series. These reversals occur over time scales on the order of several days to about two weeks. There is some indication of a seasonal signal as water generally flows into Blackwater Sound during fall, winter and early spring months, then out of Blackwater Sound in late spring and summer. From the beginning of the record until mid May there is a net transport into Blackwater Sound of approximately 82 million cubic meters of water. This corresponds to an average volume transport of approximately 4.5 m^3 s^{-1} over this time period. From mid May to late September the net transport reverses and is out of Blackwater Sound at an average rate of 12.5 m^3 s^{-1}. The long-term flow reverses again over the last 11 weeks of the study and there is a strong inflow into Blackwater Sound that averages 21.2 m^3 s^{-1} over this time period. A comparison of local winds and along-channel flow indicates that wind stress is largely responsible for the low-frequency flow observed in Jewfish Creek (see the end of the Results section of this report for details of the wind analysis).

Although impossible to see in this very long time series, tidal exchanges through Jewfish Creek are significant. Harmonic analysis quantifies the amplitude of the M_2 tidal constituent at 26.7 m^3 s^{-1}. Thus, over half of any average M_2 tidal cycle 380 x 10^3 m^3 of water moves through this channel past the study site. The interaction of the rise and fall in water level with the ebb and flood of the tide results in a tide-induced residual transport into Blackwater Sound that averages 0.79 m^3 s^{-1}.

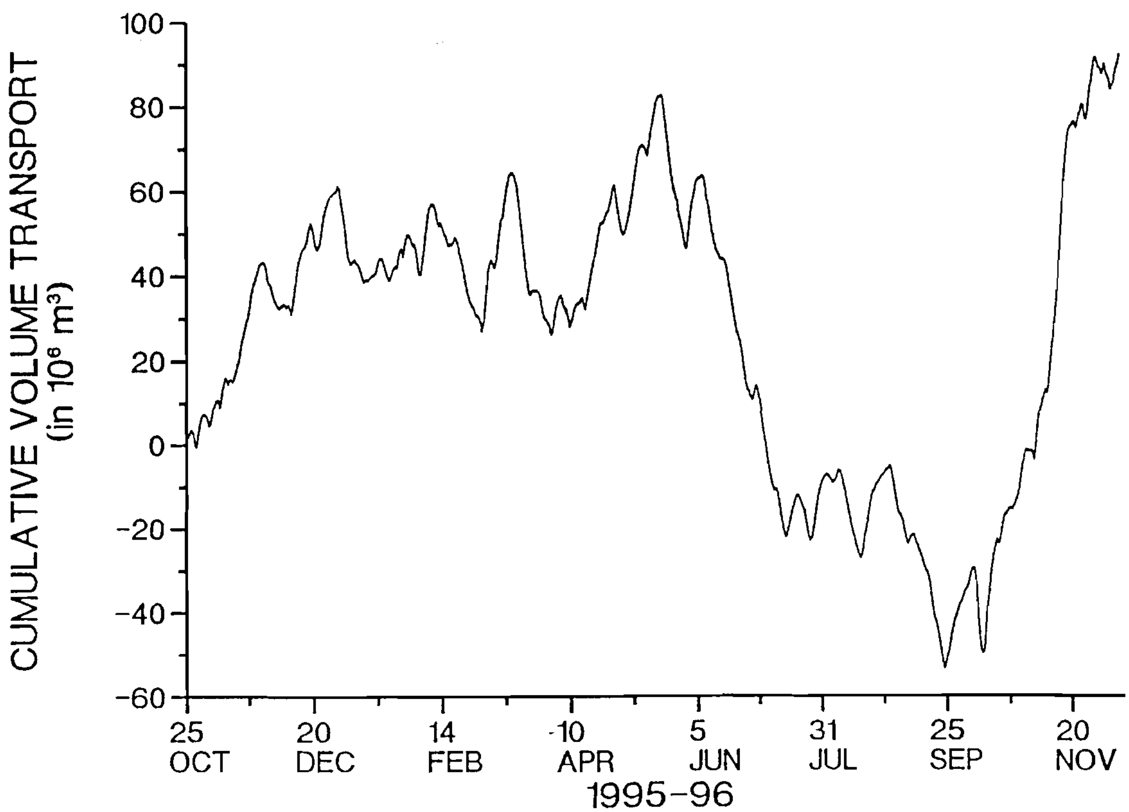

Figure S96JFC. Salinities (psu) recorded in Jewfish Creek from February 1 to June 18, 1996. Data were recorded 1 m above the bottom in 3.5 m of water near mid-channel.

The plot shows a quasi-steady increase in salinity from just over 24 at the beginning of the record to just over 30 by mid June. This represents an average increase in salinity of 0.3 per week over this four and a half month study period. Low-frequency fluctuations of 1-3 psu occurring over time scales of 3-10 days appear throughout the record. The high-frequency variability that is superimposed onto the low-frequency fluctuations generally ranges between 0.5 and 1.5. These high-frequency fluctuations reflect salinity differences between Blackwater Sound and Barnes Sound. A comparison of salinities and along-channel currents in Jewfish Creek shows that lower salinities are usually associated with flow out of Blackwater Sound. When hourly salinity values were lagged 2 hours behind the along-channel current time series a correlation coefficient of 0.164, significant above the 99% confidence level, was calculated.

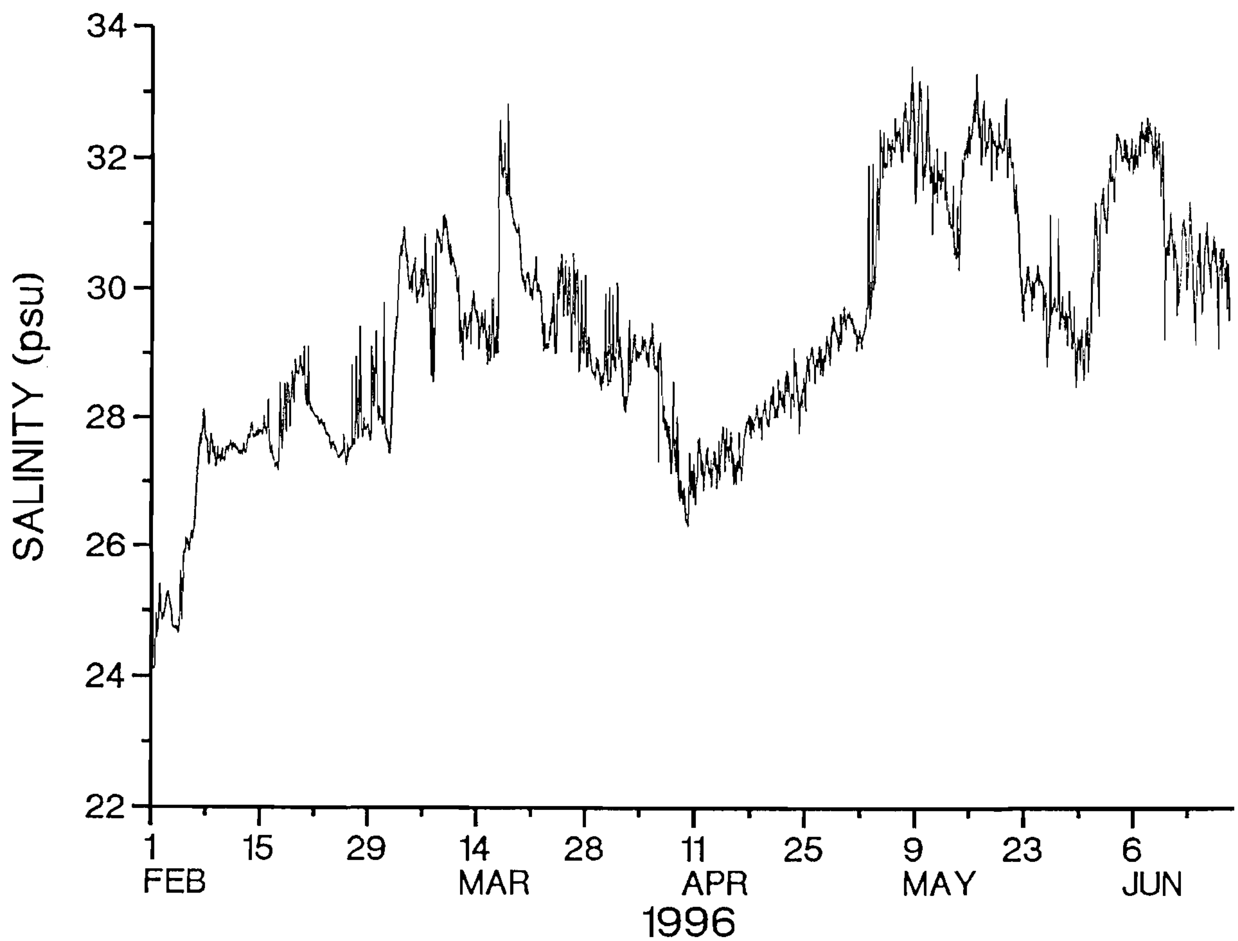

Figure T96JFC. Water temperatures (°C) recorded 1 m above the bottom in 3.5 m of water in Jewfish Creek. Data were recorded hourly from October 25, 1995 to December 12, 1996.

The plot shows the annual temperature cycle for this area of the Florida Keys. The record begins during the middle of fall cooling with temperatures near 28°C and over the next 9 weeks temperatures decrease at an average of 1.6°C per week. Temperatures reach a minimum of 14°C near the end of December, presumably with the passage of a winter cold front. For the next 3 months temperatures generally remain within about 5°C of 21°C. The passage of cold fronts are reflected in the rapid decrease in temperatures of 8-10°C followed by a gradual warming period. Seasonal warming begins around mid March and for the next 4 months temperatures increase on average 0.9°C per week. During July, August and most of September temperatures remain within 2°C of 31°C. Fall cooling begins again in late September. The passage of the season's first two cold fronts are reflected in the sudden decrease in temperatures in early November and early December.

Low-frequency fluctuations of 2-9°C occur over time scales of 1-2 weeks throughout the 414-day study period and are caused by changing weather patterns. Not surprisingly, the largest of the these fluctuations occur during fall and winter months. Superimposed onto the seasonal and low-frequency variations are high-frequency temperature fluctuations of about 1°C. These are primarily a result of local diurnal warming and cooling, but they may include the effects of tidal exchanges between Blackwater Sound and Card Sound.

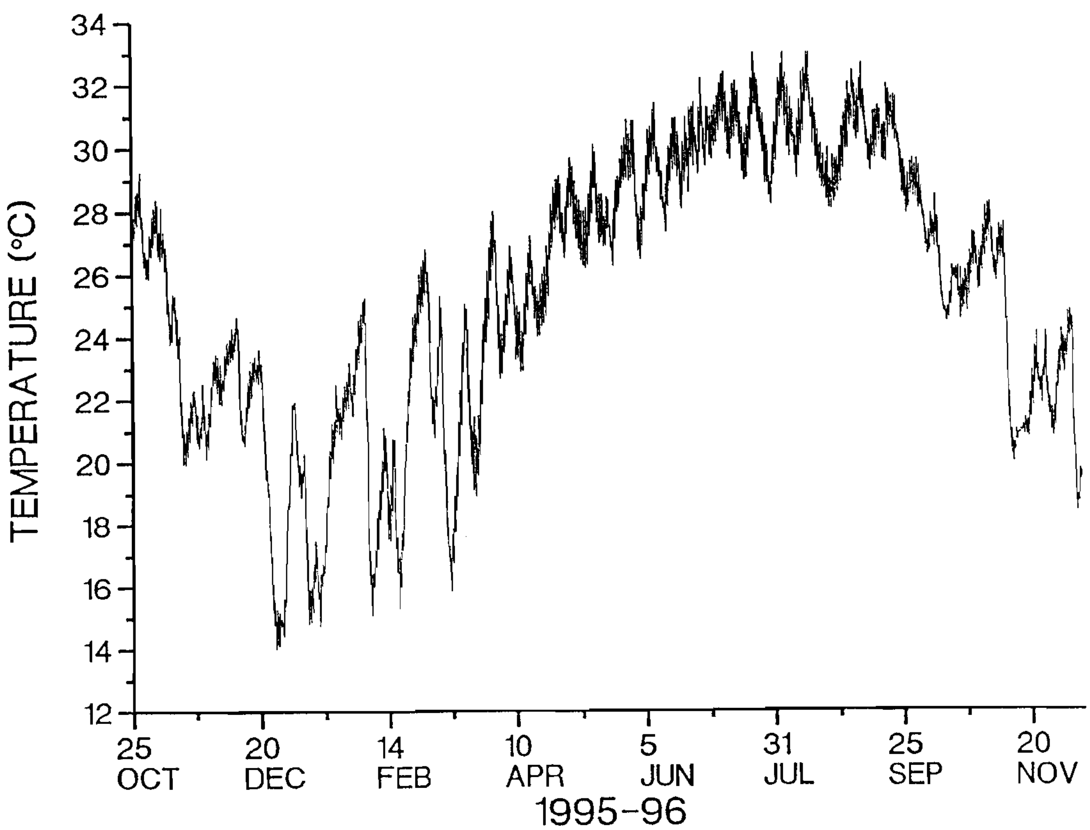

Figure CND96TC. Cumulative net displacement diagram of the along-channel current components recorded in Tavernier Creek, a tidal channel connecting northeastern Florida Bay with Hawk Channel on the Atlantic Ocean side of the Florida Keys (see **Figure 1** for station location). Data were recorded hourly in mid channel 1 m above the bottom in 3.5 m of water from October 25, 1995 to December 9, 1996. Negative displacements indicate flow toward 110°, or out of Florida Bay.

The plot shows a long-term net flow out of Florida Bay that a linear regression indicates averages 3.6 cm s^{-1} over this 411-day study period. Temporary reversals in the outflow occur repeatedly throughout the record and generally occur over time scales of a few days. There are three time periods when flow into Florida Bay is sustained for periods longer than 2 weeks. These include from mid April to mid May, mid July to early August and mid October to mid November. A comparison of local wind data and along-channel flow indicates that wind stress is largely responsible for the low-frequency variability observed in the along-channel flow (see the end of the Results section in this report for details of the wind analysis).

Although they are impossible to see in this nearly 14-month time series tidal ebbs and floods dominate the instantaneous current. The amplitude of the M_2 tidal constituent was determined by harmonic analysis to be 40 cm s^{-1}. See **Table 1** for a list of amplitudes and phase angles for the principal tidal constituents.

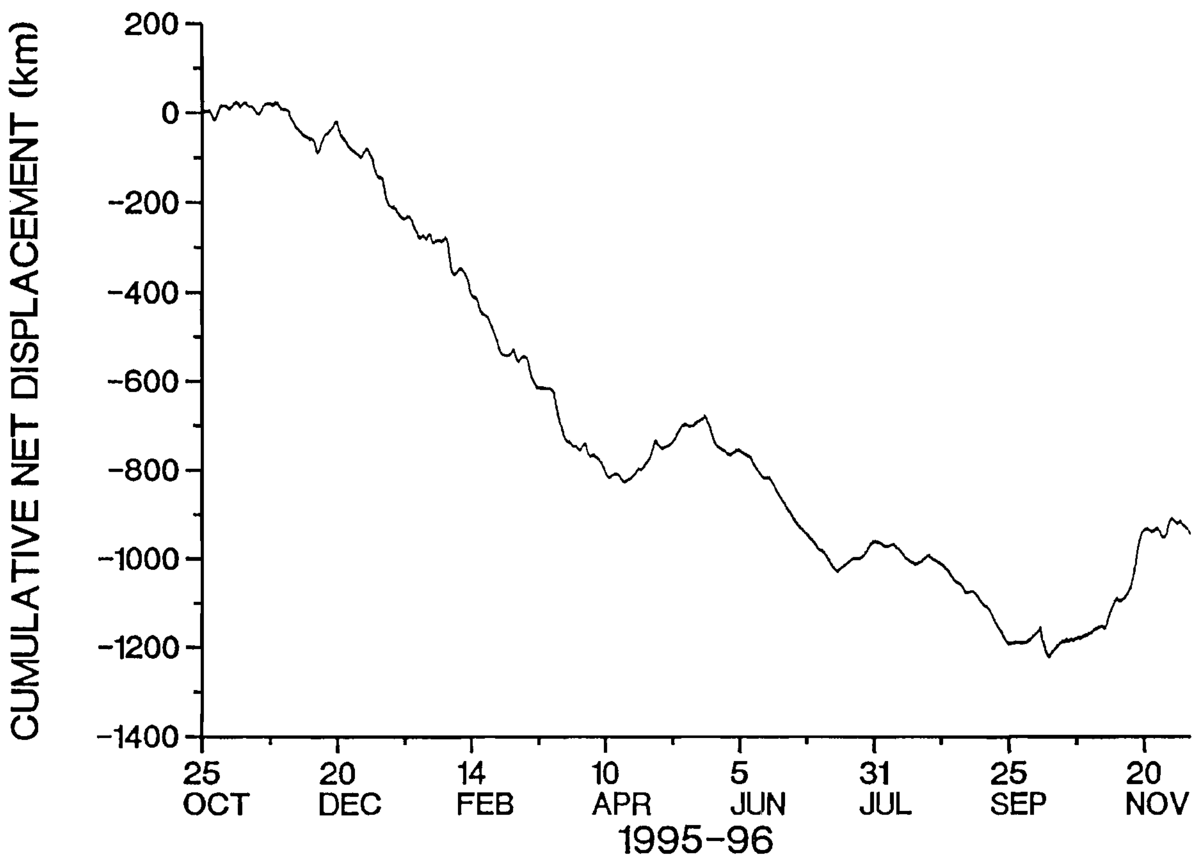

Figure NC96TC. Nontidal, along-channel current components from Tavernier Creek (see **Figure 1** for station location). Currents were recorded near mid channel 1 m above the bottom in 3.5 m of water October 25, 1995 to December 9, 1996. Current speeds and directions were decomposed into along-channel and across-channel components, then the along-channel components were smoothed with a numerical filter to remove the ebb and flood of the tide. Negative values indicate flow toward 110°, or out of Florida Bay.

The plot shows a seasonal pattern in the low-frequency, nontidal currents. Nontidal along-channel current speeds commonly fluctuate 10-30 cm s^{-1} over time scales of 1-3 days during fall, winter and early spring months. These low-frequency fluctuations are generally only 5-10 cm s^{-1} during the extended summer season. A maximum inflow to Florida Bay occurred in early November 1996 with a burst of over 30 cm s^{-1}, while a maximum nontidal outflow of nearly -50 cm s^{-1} occurred in early February. The standard deviation of the along-channel components is 10.4 cm s^{-1}. Further analysis indicates that nontidal currents account for 31% of the total variance in the along-channel flow in Tavernier Creek.

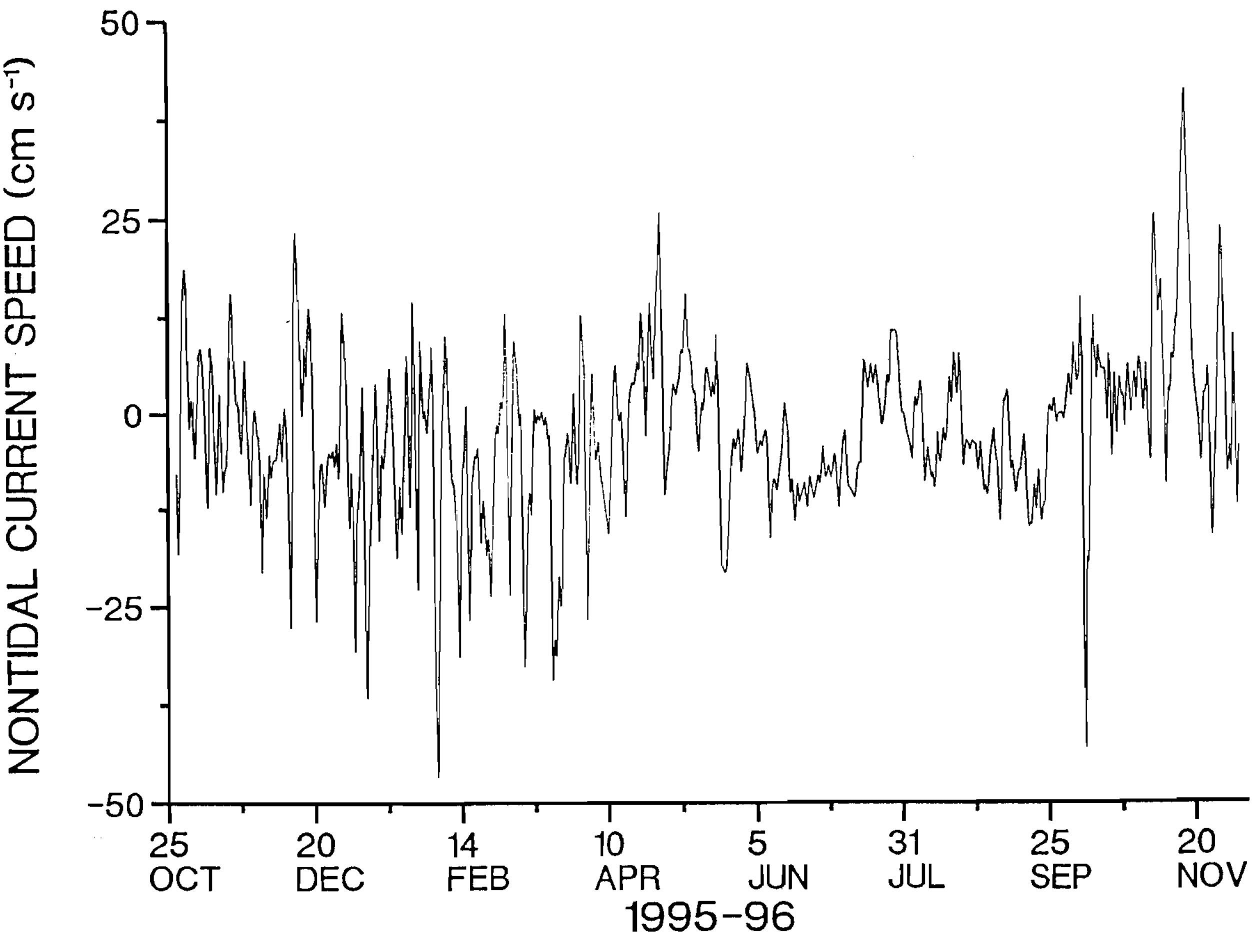

Figure CVT96TC. Cumulative volume transport through Tavernier Creek from October 25, 1995 to December 9, 1996 (see **Figure 1** for station location). A descending curve indicates a net movement of water from Florida bay into Hawk Channel. See the Results section of this report for details of how volume transport calculations were made.

The plot shows a long-term net volume transport out of Florida Bay that averages 3.7 m^3 s^{-1} over this 411-day study period. Low-frequency reversals in outflow occur repeatedly throughout the record. Generally, these reversals occur over time scales of a few days, however there are three periods when inflow to the bay is sustained for periods longer than three weeks. These include mid April to late May, mid July to early August and mid October to early December. A comparison of along-channel volume transport and local winds indicates that wind stress is largely responsible for the low-frequency variability observed in the along-channel flow (see the end of the Results section of this report for details of this analysis).

Although they are difficult to see in this very long time series, tidal exchanges between Hawk Channel and Florida Bay are superimposed onto the long-term outflow and low-frequency fluctuations. Harmonic analysis quantifies the amplitude of the M_2 tidal constituent at 53.0 m^3 s^{-1}. Thus, over each half M_2 tidal cycle 755 x 10^3 m^3 of water moves through this channel past the study site. Further analysis indicates that the interaction of the rise and fall in water level with the ebb and flood of the tide results in a tide-induced residual transport of water into Florida Bay that averages 103 x 10^3 m^3 day^{-1}.

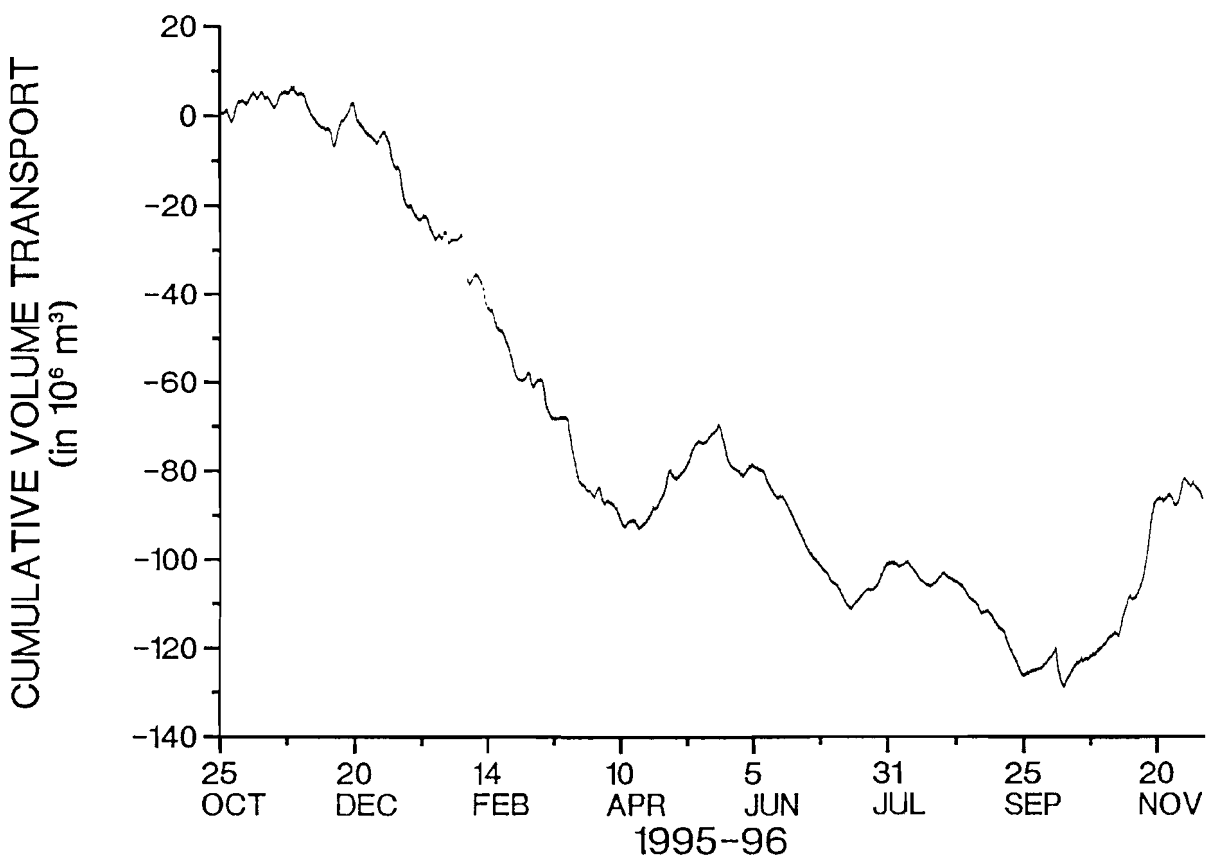

Figure S96TC. Salinity recorded 1 m above the bottom in 3.5 m of water in Tavernier Creek (see **Figure 1** for station location). Data were recorded hourly from October 25, 1995 to June 19, 1996.

The plot shows a salinity pattern that is dominated by large fluctuations over the semidiurnal time scales, reflecting tidal exchanges between the northeastern region of Florida Bay and Hawk Channel on the Atlantic Ocean side of the Florida Keys. These high-frequency fluctuations generally range between 4 and 10 psu and underline the large differences in salinities between this region of Florida Bay and the Atlantic. A comparison of salinities with along-channel currents indicates that below average salinities are consistently associated with water ebbing out of Florida Bay. Low-frequency fluctuations of 3 to 11 psu occur over time scales of several days to about 2 weeks and appear repeatedly throughout the record. Over the longer time scales the record shows a quasi-steady increase in average salinities from 29 to 38 psu from late February to early May. During the final 3 weeks there is an average decrease of about 1 psu week^{-1}.

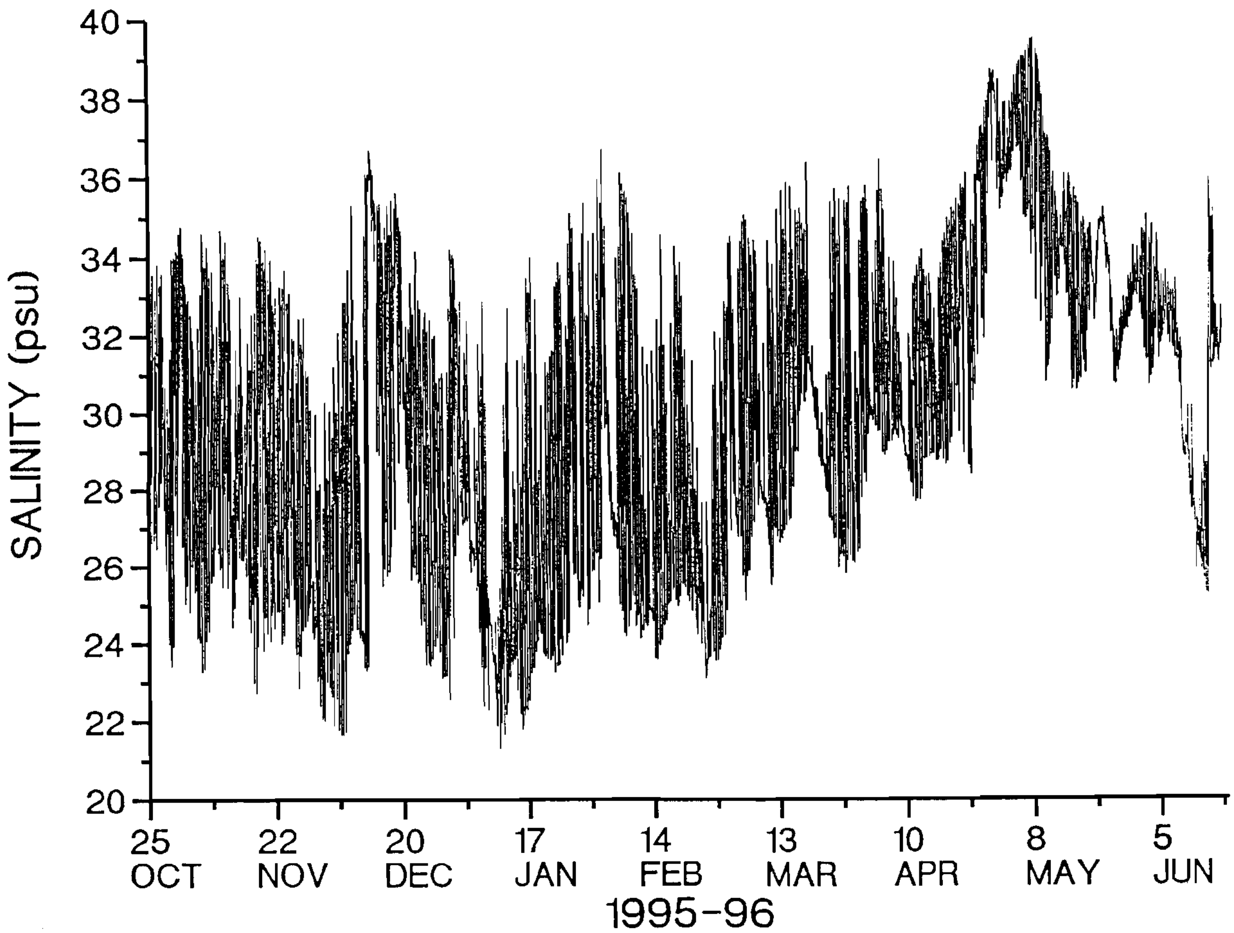

Figure T96TC. Water temperatures (°C) recorded 1 m above the bottom in 3.5 m of water in Tavernier Creek. Data were recorded hourly from October 25, 1995 to December 9, 1996.

The plot shows an annual temperature cycle nearly identical the one recorded in Jewfish Creek over the same time period (see **Figure T96JFC**). The record begins during the middle of fall cooling with temperatures near 28°C and over the next 9 weeks temperatures decrease at an average of 1.6°C per week. Temperatures reach a minimum of nearly 13°C near the end of December, presumably with the passage of a winter cold front. For the next 3 months temperatures generally remain within about 5°C of 21°C. The passage of cold fronts are reflected in the rapid decrease in temperatures of 8-10°C followed by a gradual warming period. Seasonal warming begins around mid March and for the next 4 months temperatures increase on average 0.9°C per week. During July, August and most of September temperatures remain within 2°C of 31°C. Fall cooling begins again in late September. The passages of the season's first cold fronts are reflected in the sudden decrease in temperatures in early November and early December.

Low-frequency fluctuations of 2-9°C occur over time scales of 1-2 weeks throughout the 414-day study period and are caused by changing weather patterns. Not surprisingly, the largest of the these fluctuations occur during fall and winter months. Superimposed onto the seasonal and low-frequency variations are high-frequency temperature fluctuations of 2-3°C. These are a result of local diurnal warming and cooling, but they probably include the effects of tidal exchanges between northeastern Florida Bay and the deeper, more open waters of Hawk Channel on the Atlantic Ocean side of the Florida Keys.

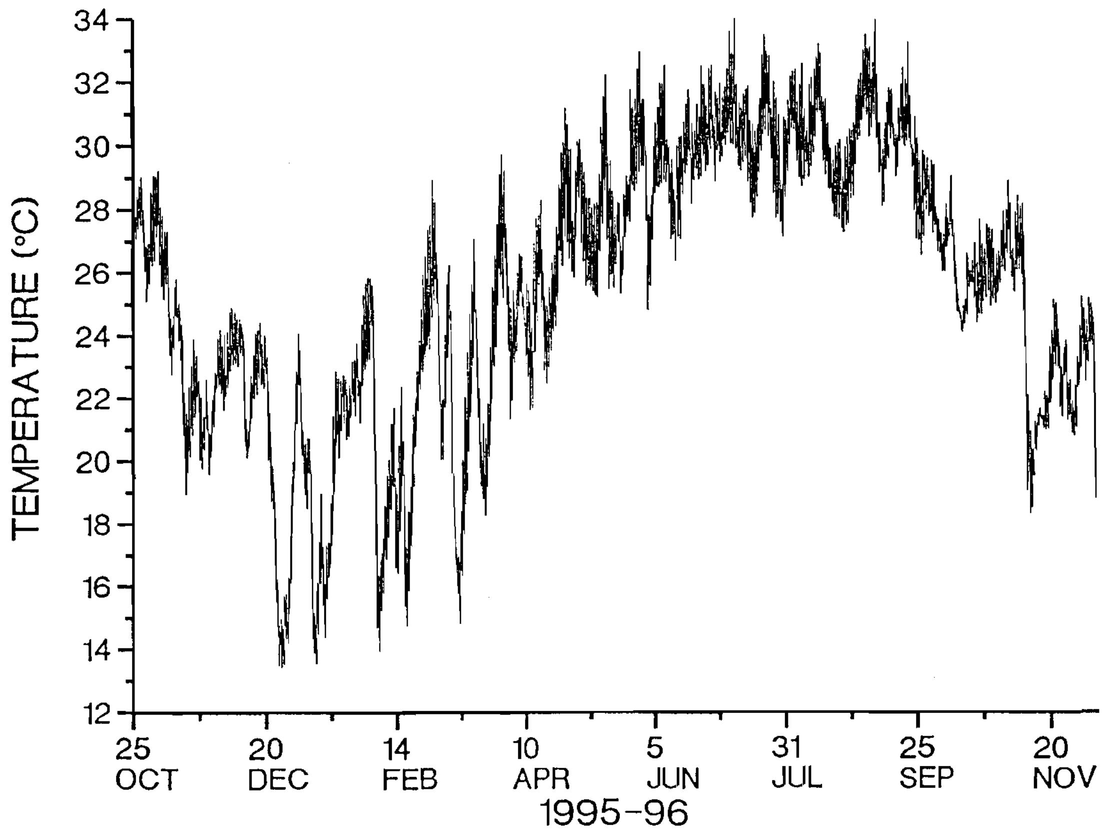

Figure CND96FLM. Cumulative net displacement of along-channel current components at a study site in Florida Bay just south of Flamingo (see **Figure 1** for station location). Data were recorded hourly from September 14, 1995 to January 30, 1996. The current meter was moored 1 m above the bottom in 3 m of water. Positive displacements indicate a flow of water toward 263°, or out of the interior of Florida Bay.

The long-term pattern can be broken into two parts. For the first eight weeks of the study there was a relatively strong quasi-steady outflow from Florida Bay that averaged 4.6 cm s^{-1}. During this time low-frequency fluctuations appear as temporary reversals or subtle variations in the outflow rate and generally last 2-4 days. During the last 12 weeks outflow continued but at a much slower rate (0.9 cm s^{-1}). Low-frequency reversals during this time period may last up to 10 days. These differences in the two halves of the record may indicate a seasonal change in the long-term flow pattern for this region of Florida Bay.

Displacements associated with the ebb and flood of the tide are superimposed onto both the long-term outflow and low-frequency variations. The amplitude of the M_2 tidal constituent was determined by harmonic analysis to be 35 cm s^{-1}. See **Table 1** for a list of amplitudes and phase angles for the principal tidal constituents.

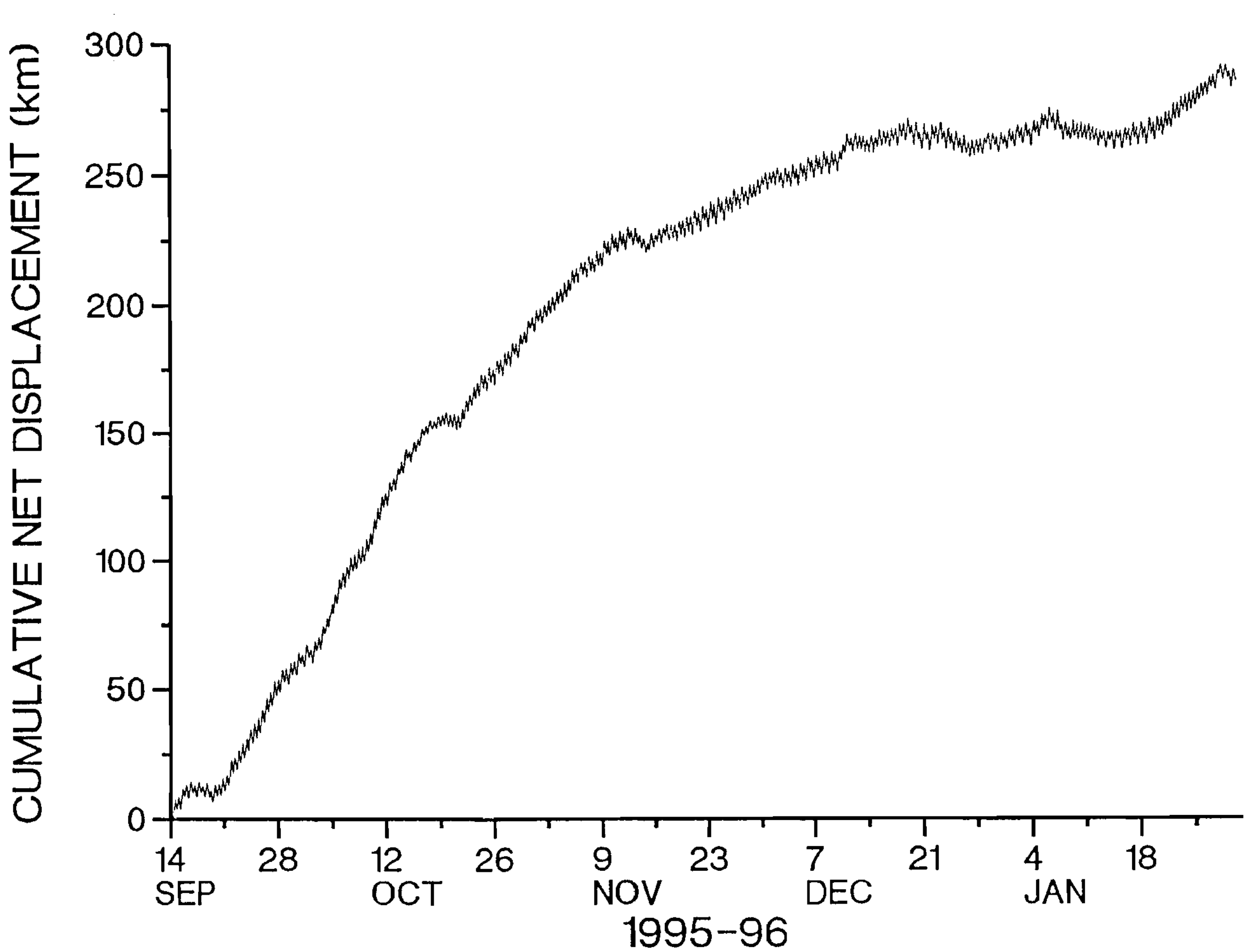

Figure NC96FLM. Nontidal, along-channel current components from the study site in Florida Bay just south of Flamingo (see **Figure 1** for station location). Currents were recorded 1 m above the bottom in 3 m of water from September 14, 1995 to January 30, 1996. Current speeds and directions have been decomposed into along-channel and across-channel components, then the along-channel components were smoothed with a numerical filter to remove high-frequency variability including the ebb and flood of the tide. Positive values indicate flow toward 263°, or out of the interior of Florida Bay.

The pattern of the along-channel, nontidal current shows that flow remains predominately positive throughout most of the four and a half month study period, indicating a quasi-steady outflow from Florida Bay (see **Figure CND96FLM**). A general reduction in low-frequency outflow and more frequent occurrences of inflow during most of November, December and January suggest a seasonal change in long-term flow in this region of Florida Bay. Along-channel speeds generally fluctuate 2-7 cm s^{-1} over time scales of 2-3 days. Nontidal outflow is sustained at over 2 cm s^{-1} for most of the first 8 weeks of the study period and reaches a maximum of nearly 12 cm s^{-1} in mid October. Temporary reversals in the outflow occur through the study period, attaining a maximum inflow rate of over 5 cm s^{-1} in early January. The standard deviation of the low-pass filtered, along-channel component is 2.9 cm s^{-1}.

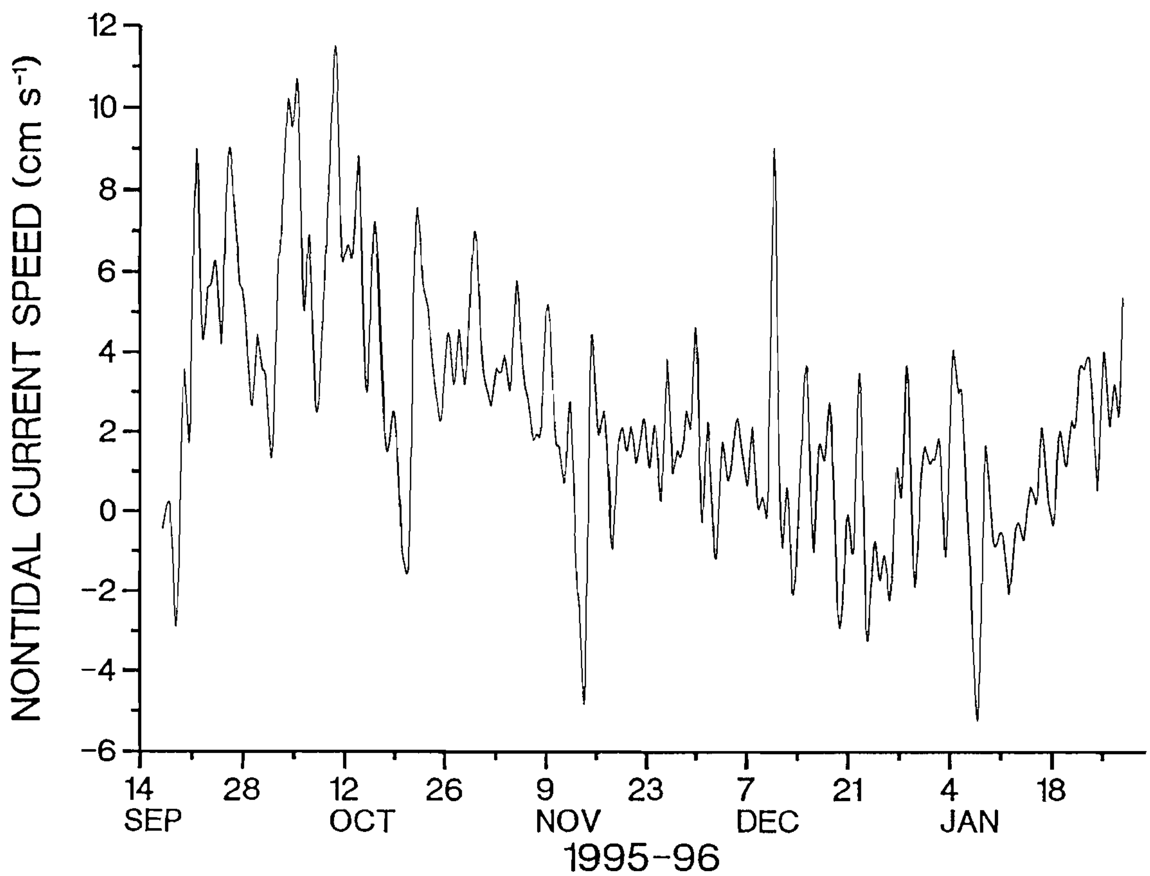

Figure CVT96FLM. Cumulative volume transport through the east-west channel just south of Flamingo in northern Florida Bay (see **Figure 1** for station location). Data were recorded hourly from September 14, 1995 to January 30, 1996. The current meter was moored 1 m above the bottom in approximately 3 m of water. Positive volume transport indicates a flow of water toward 260°, i.e., toward the Gulf of Mexico. See the Results section of this report for how volume transport calculations were made.

The plot shows a quasi-steady transport of water out of the interior of Florida Bay during the first 8 weeks of the study period. The average outflow during this time was 28.3 $m^3\ s^{-1}$. From the middle of November to the end of the record the flow reverses and there is a quasi-steady inflow to the bay that averages 15.0 $m^3\ s^{-1}$. Low-frequency fluctuations occur repeatedly throughout the record and are characterized as temporary reversals or subtle variations in the inflow to or outflow from the bay and occur over time scales on the order of several days to about a week.

Superimposed onto the long-term and low-frequency patterns are the ebb and flood of the tide. The amplitude of the M_2 constituent is 438 $m^3\ s^{-1}$, indicating that over six million cubic meters of water move through this channel during each half tidal cycle. The interaction of the rise and fall in water level with the ebb and flood of the tide results in a tide-induced transport of water into the bay which averages 27.6 $m^3\ s^{-1}$. A comparison with **Figure CND96FLM** shows that when low-frequency nontidal forcing is weak, as during the last 12 weeks of the study, volume transport into the Florida Bay by tidal pumping dominates the flow through this channel.

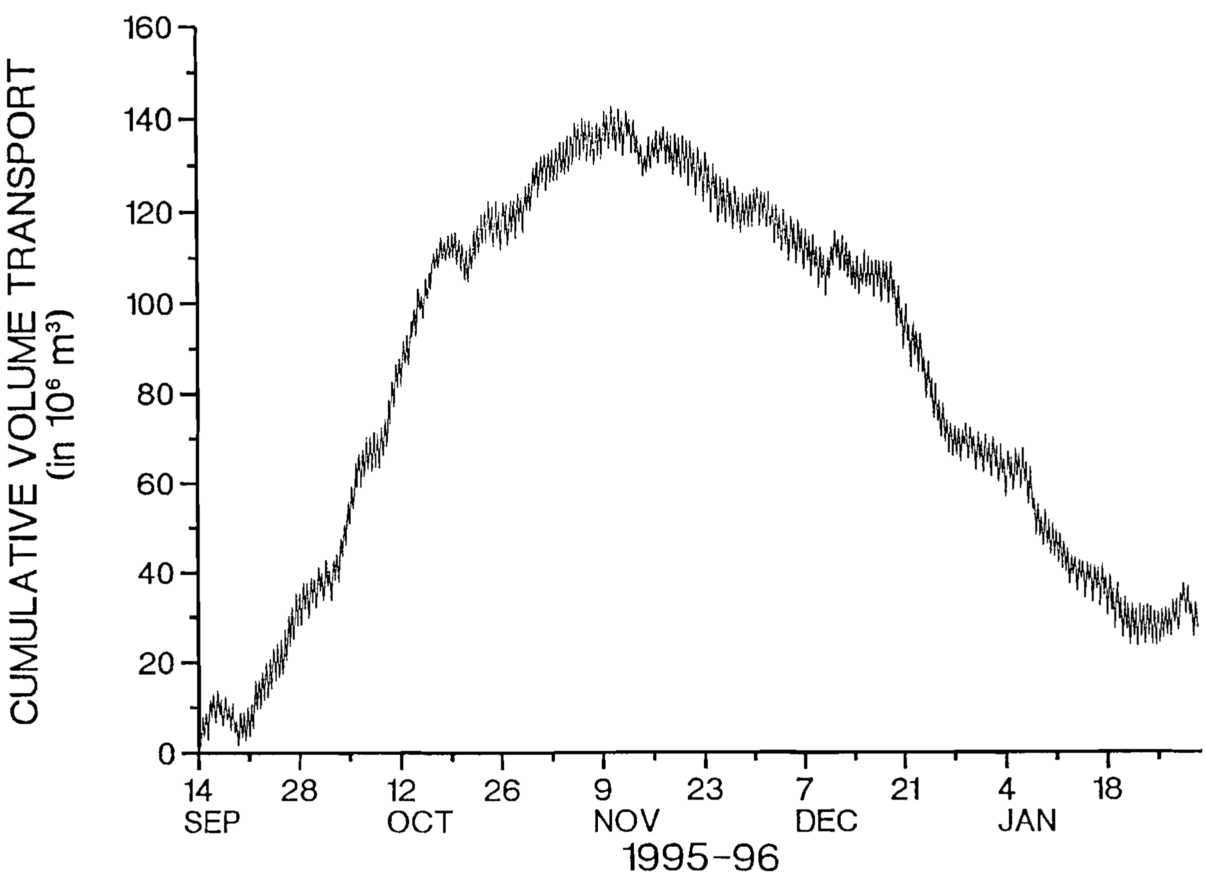

Figure T96FLM. Water temperatures (°C) recorded 1 m above the bottom in 3 m of water at the study site in Florida Bay just south of Flamingo (see **Figure 1** for station location). Data were recorded hourly from September 14, 1995 to January 30, 1996.

The plot shows the pattern of fall cooling and mid-winter temperatures for this area of Florida Bay. The plot begins with temperatures at or near the seasonal maximum of 32°C. Fall cooling begins during the fourth week of September and for the next 14 weeks temperatures decrease at an average rate of just over 1°C per week. Temperatures reach a minimum of nearly 12°C during the second week of January, presumably due to the passage of a winter cold front. A warming trend is recorded during the final 3 weeks of the study period during which temperatures increase by approximately 9°C. Low-frequency fluctuations are generally around 2°C during the first half of the study but increase by 2 to 4-fold during the late fall and early winter time period.

Superimposed onto the seasonal and low-frequency variations are high-frequency temperature fluctuations of 1-3°C which primarily reflect local diurnal warming and cooling. However, there is some indication during the cooling events recorded in late December and early January that these high-frequency fluctuations include the effects of tidal exchanges between sub-basins in the interior of Florida Bay and the deeper, more open waters to the west.

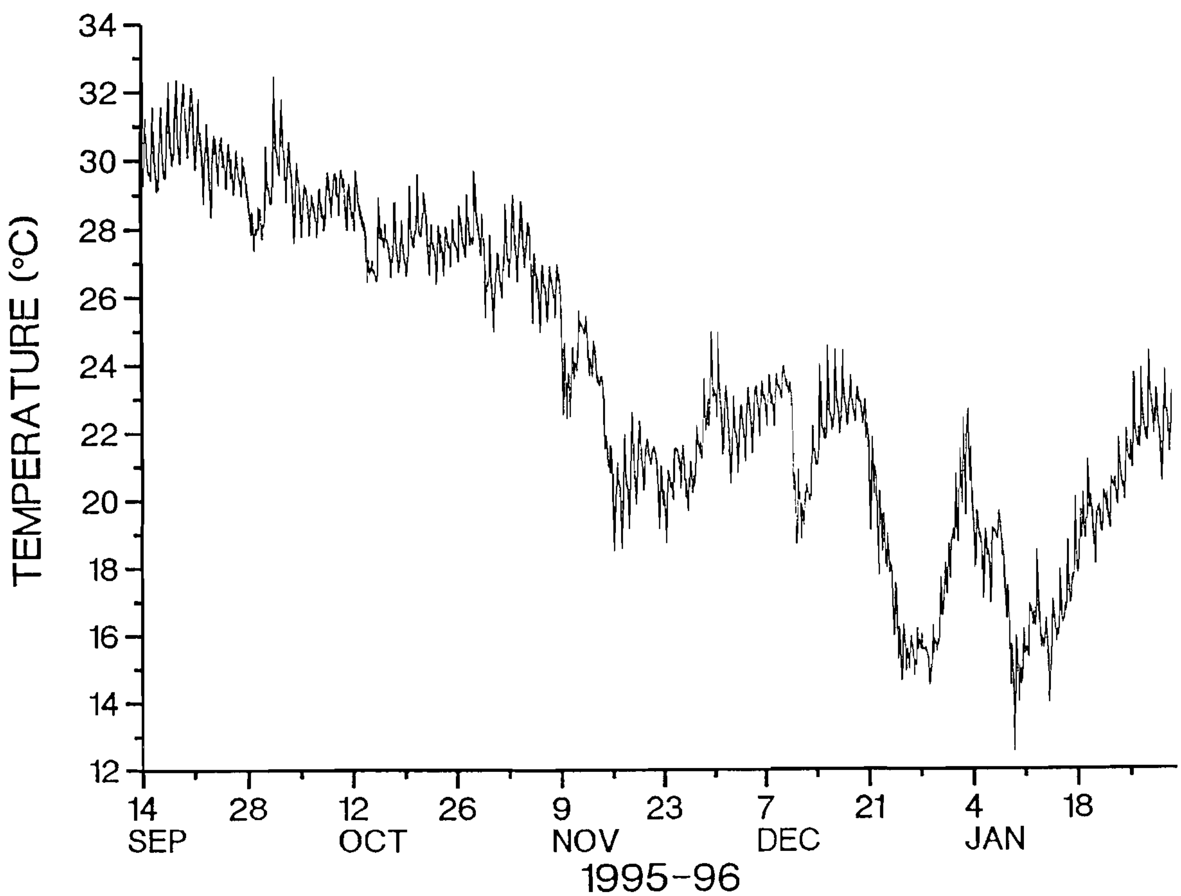

Table 1. Harmonic constants (amplitudes, η, in cm s^{-1}; local phase angles, κ, in degrees) of the principal tidal constituents for the along-channel current components from Jewfish Creek, Tavernier Creek and from a study site in the main channel just south of Flamingo in Florida Bay.

Study Site		M_2	S_2	N_2	K_1	O_1	P_1
Jewfish Creek	η κ	22.8 025.9	2.0 051.7	4.1 001.6	2.8 272.2	3.4 311.7	0.6 274.6
Tavernier Creek	η κ	40.1 235.4	6.0 261.6	7.5 213.1	5.4 245.3	5.9 242.2	1.8 230.8
Flamingo	η κ	35.6 206.3	9.1 237.4	5.3 198.6	7.5 118.5	6.3 116.3	2.5 118.5

Table 2. Channel geometry at the three study sites in Jewfish Creek, Tavernier Creek and the study site in the main channel just south of Flamingo. Cumulative net along-channel displacements are calculated from currents observed 1 m above the bottom. Volume transport was calculated using a time-varying cross-sectional area and a depth-integrated current speed. Calculations for Jewfish Creek are for October 25, 1995 to December 12, 1996; October 25, 1995 to December 9, 1996 for Tavernier Creek and September 14, 1995 to January 30, 1996 for the Flamingo site. Positive values indicate a flow into Florida Bay through Jewfish Creek and Tavernier Creek, and outflow through the channel south of Flamingo. The M_2 volume transport is the amount of water passing the study site during the flood or ebb half of an M_2 tidal cycle.

	Jewfish Creek	Tavernier Creek	Flamingo Site
Channel Width (m)	36	67	525
Mean Depth (m)	3.4	1.9	2.6
Mean Cross-sectional Area (m^2)	122.6	130.5	1354.5
Net Displacement (km day^{-1})	0.9	-2.3	1.9
Amplitude of M_2 Volume Transport (m^3 s^{-1})	26.7	53.0	438.4
M_2 Volume Transport (10^3 m^3)	380.2	754.7	6242.9
Mean Transport by Tidal Pumping (10^3 m^3 day^{-1})	68.6	103.2	-2388.0

The analysis of wind data from Molasses Reef shows that the 040°-220° component of wind stress is most highly correlated with along-channel volume transport through Jewfish Creek (correlation coefficient, $r = 0.5768$). Spectral analysis indicates a coherence significant at the 99% confidence limit (Panofsky and Brier, 1958) between along-channel volume transport and this component of wind stress at 36 hours and over all time scales greater than 2 days. The highest coherence (0.604), significant above the 99.9% confidence level, occurs at a periodicity of 128 hours. Thus, at periodicities of 5 days wind stress accounts for 60% of the variance in along-channel volume transport through Jewfish Creek. Phase spectra indicate that at the 36-hour periodicity the phase lead of wind stress over along-channel flow is 330°. At periodicities of 2-26 days the phase lead ranges from 0-30°. Thus, wind stress forcing has a time lead of 0-33 hours over along-channel flow. The magnitude of the transfer function indicates that a 1 dyne cm^{-2} wind stress out of the northeast (corresponding to an 18 mile hr^{-1} wind speed) produces a 42 $m^3\ s^{-1}$ volume transport through Jewfish Creek.

Flow in Tavernier Creek is most highly correlated with the 100°-280° component of wind stress ($r = 0.2242$). Coherence spectra show highly significant coherence (above the 99.9% confidence limit) between winds out of the east-southeast and along-channel flow over all time scales greater than 2 days. Highest coherence (0.523) occurs at a periodicity of 106 hours, indicating that winds account for over half the variance in along-channel volume transport through Tavernier Creek over the 4-5 day time scale. Phase spectra show that the response of along-channel flow to wind forcing lags by 2-3 hours at that time scale. Transfer function spectra indicate that at the 106-hour periodicity a wind stress of 1 dyne cm^{-2} out of the east-southeast produces an along-channel flow through Tavernier Creek of about 24 $m^3\ s^{-1}$.

Results of spectral analyses for Long Key winds and flow through the channel south of Flamingo indicate that the 090° component of the wind is most closely coupled with along-channel volume transport. Statistically significant coherence (above the 95% confidence limit) was calculated at periodicities of 32-35 hours and at 64-80 hours. Highest coherence ($r = 0.544$) occurs at a periodicity of 64 hours which indicates that over half of the variance in the along-channel flow is accounted for by easterly wind stress over the 2-3 day time scale. Phase spectra indicate that along-channel flow lags the onset of wind forcing by 4-21 hours, with longer lags occurring over longer time scales. Calculations of the transfer function show that at a periodicity of 64 hours a 1 dyne cm^{-2} wind stress produces a volume transport of 135 $m^3\ s^{-1}$.

DISCUSSION

Results from this third phase of the study of physical processes in Florida Bay extend our understanding of regional circulation patterns both northward and northeastward into previously unstudied parts of the bay. Also, our results provide new information regarding the relative importance of tide and wind forcing in explaining the long-term net transport through the bay.

Tidal currents recorded in Jewfish Creek (see **Table 1**) were unexpectedly strong, given the isolation of the study area from shelf waters and the negligibly small tidal rise and fall in water level. Tidal water level amplitudes in Barnes Sound are greatly damped, because tidal waves entering the sound from the Atlantic must first pass through narrow channels to enter Card Sound, then through narrow channels between Card Sound and Barnes Sound. Analysis of water level data from the northeastern part of Florida Bay, including Blackwater Sound, revealed virtually tideless conditions in this area (Smith and Pitts, 1994). A harmonic analysis of bottom pressures recorded at the Jewfish Creek study site revealed an M_2 amplitude of only 3.5 cm.

Nevertheless, tidal exchanges through Jewfish Creek are significant. The M_2 amplitude is 23 cm s^{-1}, and the associated volume transport between Barnes Sound and Blackwater Sound reaches 26 m^3 s^{-1}. The total exchange over any half M_2 tidal cycle is 380 x 10^3 m^3. For comparison, the volume of Blackwater Sound is approximately 72 x 10^6 m^3. Thus, M_2 tidal constituent exchanges through Jewfish Creek vary the volume of Blackwater Sound by about 0.5%. Tidal pumping is significantly less. The mean pumping rate of 0.79 m^3 s^{-1} is equivalent to approximately 11.3 x 10^3 m^3 per M_2 tidal cycle. This is significant, however, because it is a one-way transport process that does not depend upon tidal mixing, and it is dependable as it is periodic. But it is a very small fraction of the total exchange. At this rate, the tidal pumping mechanism will exchange approximately 0.09% of the volume of Blackwater Sound per day and nearly 3 years would be required to renew the volume of Blackwater Sound entirely.

The tidal exchange process that cannot be quantified with the available data base is the net exchange of water between Barnes Sound and Blackwater Sound due to tidal mixing. Without detailed hydrographic data involving a conservative tracer, it is impossible to determine how much of the water that has just passed through Jewfish Creek returns on the following half tidal cycle.

The strong nontidal currents recorded in Jewfish Creek were unexpected as well. Statistics indicate that these low-frequency, nontidal currents account for nearly 80% of the total variance in along-channel flow. With sustained speeds of 20-30 cm s^{-1} for periods of several days (which is fairly common in Jewfish Creek), currents can exchange significant fractions of the volume in Blackwater Sound. For example, a +20 cm s^{-1} along-channel current speed translates into a volume transport of approximately +24 m^3 s^{-1} through the channel. If sustained for 2-3 days this nontidal current would transport a volume equivalent to 6-9% of the total volume in Blackwater Sound.

Results from spectral analyses indicate that the low-frequency variability in flow through Jewfish Creek is closely coupled with local wind forcing over all time scales greater than 2 days. A coherence of 0.604 was calculated at the 5-day periodicity which indicates that at that time scale winds account for 60% of the variance in along-channel flow. Currents respond primarily to the 040° component of wind stress which is likely due to the northeast-southwest orientation of Card Sound, Barnes Sound and Blackwater Sound. Taking into account the fact that prevailing winds during fall and winter months are primarily from the northeast quadrant, this orientation of inland water bodies would encourage transport from Barnes Sound into Blackwater Sound.

A comparison of salinity recorded in Jewfish Creek and flow past the study site provides some insight into how salt and fresh water are imported into and exported from the northwest corner of the bay. The 138-day time series of salinity and along-channel currents from Jewfish Creek indicate that decreases in salinity coincide with flow out of Blackwater Sound. A correlation coefficient of 0.164, significant above the 99% confidence limit, occurs when salinity is lagged 2 hours behind the onset of along-channel flow. This indicates that more freshwater is entering Blackwater Sound than Barnes Sound despite the fact that the C-111 Canal discharges directly into Barnes Sound. Thus, it appears that Jewfish Creek provides a conduit for freshwater leaving the northeast corner of Florida Bay. Perhaps as importantly it serves to import salt into the bay to maintain brackish water conditions there.

A similar analysis for Tavernier Creek shows that tidal pumping is directed into Florida Bay at a rate of approximately 1.2 $m^3 s^{-1}$, which is equivalent to 17.0 x 10^3 m^3 per M_2 tidal cycle. The M_2 amplitude of 53 $m^3 s^{-1}$ translates into a total volume transport of 755 x 10^3 m^3 over any half M_2 tidal cycle. Even with modest mixing rates at both ends of the channel, localized tidal motions may be the dominant exchange mechanism between Florida Bay and Hawk Channel through Tavernier Creek. **Figure S96TC** offers evidence that this may be happening. The mean salinity range recorded at the study site over each semidiurnal tidal cycle is about 7 during the first 6 months of the record and somewhat less during the last two months. A comparison of salinities and along-channel currents indicates that below average salinities tend to be associated with ebb currents. Thus, it is clear that the same water is not moving back and forth through Tavernier Creek. Rather, some fraction of the relatively high salinity Hawk Channel water entering Florida Bay is replaced through mixing by relatively low salinity Florida Bay water that then leaves on the following ebb.

While the low-frequency, nontidal currents in Tavernier Creek are generally much weaker than those recorded in Jewfish Creek, they account for a little over 30% of the total variance in the along-channel flow. These low-frequency currents are caused primarily by winds. Spectral analysis shows highly significant coherence between winds and along-channel flow over time scales greater than two days. At a periodicity of four days, as much as half of the low-frequency variability in transport through Tavernier Creek is due to wind forcing. Along-channel flow is most coherent with the east-southeasterly (100°) wind stress component. This is the prevailing wind direction during the extended summer season, and it is a common wind direction throughout the year.

Results from the Tavernier Creek study suggest that both tidal pumping and wind stress act to force water into Florida Bay through this channel. However, the long-term flow is observed to be out of the bay and into Hawk Channel. It is likely that the same mechanism that drives the quasi-steady long-term outflow through channels in the Middle and Lower Keys (Smith, 1994; Smith and Pitts, 1995; Pitts and Smith, 1995) is forcing a long-term outflow through Tavernier Creek as well. The greater variablility in the outflow observed through Tavernier Creek compared to channels further south may be due to mangrove islands and mud banks in the northern and northeastern parts of Florida Bay which greatly restrict the movement of Gulf water through the bay and into Hawk Channel, thus making it more responsive to local forcing.

Results from the study in the channel just south of Flamingo indicate that at times flow is dominated by nontidal forcing, while at other times tidal motions control transport. From the beginning of the study to early November there was a quasi-steady outflow that resulted in a cumulative volume transport of 140 x 10^6 m^3 out of Florida Bay. During that time, nontidal currents were generally between +2-7 cm s^{-1}, and they may be responsible for the observed outflow. From mid November through January volume transport was directed into Florida Bay at an average rate of 15 m^3 s^{-1}. During that time nontidal currents were relatively weak and nearly equally distributed between positive and negative values. Thus, it appears that in the absence of significant nontidal forcing tidal pumping dominates flow through this channel.

Volume transport calculations indicate that tidal pumping at the Flamingo study site averages -27.6 m^3 s^{-1} (into Florida Bay). The total transport during the first two months of the study was 27.7 m^3 s^{-1} (out of the bay). Comparison with the tidal pumping value suggests that the total outflow would have been approximately 55 m^3 s^{-1} in the absence of tidal pumping. During the second half of the study, when nontidal currents were relatively weak, inflow to Florida Bay averaged -15.5 m^3 s^{-1}. Comparing this value with the -27.6 m^3 s^{-1} tidal pumping value suggests that another mechanism is forcing water out of the bay and opposing the local tidal pumping process.

We hypothesize that a regional-scale tide-induced residual motion is transporting water into the bay over the mud flats and out of the bay through this channel, where we had a current meter to record it. This is the same mechanism that was described for driving the outflow observed through Iron Pipe Channel, Man of War Channel and Conchie Channel which appears in our Phase Two report (Pitts and Smith, 1995). This in-over-the-flats, out-through-the-channels mechanism requires that low-tide water levels occur primarily during the ebb part of the tidal cycle. Water depths over the flats on either side of the channel may be only a few tens of centimeters at low tide, and frictional resistance is inversely related to water depth. Thus, friction acting on the temporarily shallower water column ebbing off the mud banks is greater than friction acting on the temporarily deeper water column flooding in over the mud banks. As a result more water is likely to exit through the deeper channels, producing the observed quasi-steady outflow.

As with Jewfish Creek and Tavernier Creek, the nontidal along-channel volume transport just south of Flamingo appears to be closely coupled with the local wind field. Statistically significant coherence was calculated at periodicities of 32-35 hours and again at 64-80 hours. Over these time scales wind stress accounted for roughly half of the total variance in along-channel volume transport. Results show that the 90° component of the wind is most closely coupled with along-channel flow, which is not surprising given the east-west orientation of this relatively broad channel.

To test the validity of using predicted water levels to make volume transport calculations through the channels we compared calculations made using measured water levels with those made using predicted values. For Jewfish Creek, a 176-day comparison of hour-by-hour values showed a high degree of similarity ($r = 0.998$). Over longer time scales, however, the cumulative volume transport using predicted water levels underestimated the amount of water flowing into Blackwater Sound. By the end of the 176-day study period the difference was approximately 25%. Further analysis showed that low-frequency flow into Blackwater Sound was more often associated with higher water levels. Using tidal predictions in our calculations, we exclude interactions over longer time scales, and thus we do not simulate this low-frequency pumping mechanism. Results from the 83-day study in the channel south of Flamingo also showed that volume transport calculations using predicted water levels overestimated outflow from Florida Bay, but only by 11% by the end of the study. For Tavernier Creek, using 236 days of water level data, calculations using predicted water level values overestimated the outflow from Florida Bay, but only by 6%.

Results from the circulation part of our study put in better perspective the relative importance of tidal and nontidal forcing, as well as the nature of tidal forcing. Calculations indicate that the residual tidal transport is a small fraction of the total volume exchanged on a given tidal cycle for all of the channels we studied. For example, over a half tidal cycle the volume of water transported through Tavernier Creek is approximately 754×10^3 m^3 while the residual tidal transport is only 17×10^3 m^3 over the same time period. Thus, as we have found for other tidal channels in this part of Florida Bay, the transport of dissolved and suspended substances between sub-basins within the interior of the bay, or between the interior and outlying waters, may be a result of tidal mixing as much as it is a result of the residual flow.

Temperature records were not the central focus of our circulation study, but we include results because of the important role that temperature plays in many biological and chemical processes. The temperature plots include a 4-month record showing fall cooling in northern Florida Bay; longer records show the full annual temperature cycle in the northeastern part of the bay. A visual comparison of Figures **T96JFC**, **T96TC** and **T96FLAM** indicates that low-frequency fluctuations are virtually identical. One might expect this, in view of the fact that the weather conditions that produce warming and cooling are similar over these short distances.

Higher frequency diurnal fluctuations in Tavernier Creek and near Flamingo are nearly twice those recorded in Jewfish Creek. The differences can be explained by the rapid response of nearby shallow waters to heat exchanges through the air/water interface. Relatively deeper water in Barnes Sound and Blackwater Sound, on either side of Jewfish Creek, would respond more slowly. There is some indication of a semidiurnal temperature signal in the records from Flamingo and Tavernier Creek. These reflect tidal exchanges between shallow bank water in the interior of the bay and deeper outlying water from western Florida Bay or Hawk Channel. Given the close proximity of Hawk Channel to Tavernier Creek, one might expect a more clearly defined semidiurnal signal there.

We conclude this report by addressing pertinent "key research needs" outlined in the Florida Bay Science Plan (Armentano et al., 1994) and "informational needs" listed in the Boesch Report (Boesch et al., 1993). These needs are based on topics which describe the major gaps in our present understanding of the Florida Bay ecosystem, and which form the foundation for ongoing and future work. Phase Three of our study of the physical processes of Florida Bay has contributed to an understanding of transport processes between the bay and the Gulf of Mexico to the west, and between the bay and the Atlantic Ocean to the east. This study documents for the first time exchanges between the northeastern part of Florida Bay and Atlantic Ocean through Barnes Sound and Card Sound. The long-term flow through Jewfish Creek can be characterized as a series of low-frequency reversals with little net transport over the longer time scales. Transport over the time scales of several days to a week can be substantial, however. There is some indication of a seasonal signal but it is not well defined. Unlike the quasi-steady outflow observed from the southeastern part of the bay through channels in the Middle Keys, long-term outflow through Tavernier Creek can be interrupted for weeks at a time. It is unclear at this time what causes the extended reversals, but it is likely a combination of local tidal pumping and wind stress.

Current meter data from the channel south of Flamingo documents a long-term flow out of the bay which supports findings from other tidal channels in this part of the bay. However, volume transport calculations which combine current meter data with tidal water level variations show an outflow from the bay during early fall, followed by an inflow from late fall through early winter.

One of the specific tasks in the Florida Bay Science Plan called for determining the relative importance of tides, wind and freshwater inflows on flushing rates and exchanges with adjacent water bodies. Results indicate that tidal processes are particularly important for the transport of water through the channel south of Flamingo. The interaction of the rise and fall in water level and the ebb and flood of the tide results in a tidal pumping into the bay, and possibly a tide-induced residual outflow from the bay at this location. Tidal pumping was responsible for the quasi-steady inflow that was observed from November through January. Low-frequency nontidal motions appear to be more important in Jewfish Creek, explaining the steady one-way transport of water between Blackwater Sound and Barnes Sound which can last up to two weeks. The relative importance of tidal and nontidal flow through Tavernier Creek is somewhat more difficult to determine. On the one hand, it is clear that tidal ebbs and floods are important in the transport of water through this channel. On the other hand, it is apparent that low-frequency nontidal currents play an important role in forcing water through Tavernier Creek. Our analyses indicate that the low-frequency nontidal motions in all three channels are caused primarily by local wind forcing.

Finally, both the Science Plan and the Boesch Report have called for *in situ* data covering a wide range of time scales to aid in parameterizing and verifying circulation models of Florida Bay. The results reported here complement our earlier studies which described the physical coupling of the west side of Florida Bay with the Gulf of Mexico, quantified transport through tidal channels in the interior of the bay and characterized flow through passes that connect Florida Bay with Hawk Channel. Together these data form a substantial data base that should not only prove useful to modelers but should provide information needed to make sound management decisions regarding Florida Bay.

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