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TIDAL AND LONG-TERM VOLUME TRANSPORT THROUGH JEWFISH CREEK, FLORIDA KEYS

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ABSTRACT

A 14-mo current meter record together with channel calibration measurements are used to investigate the dynamics of long-term volume transport through Jewfish Creek, the main channel connecting Blackwater Sound in northeastern Florida Bay with Barnes Sound, a southern extension of Biscayne Bay. Seasonal variations dominate the long-term flow through this channel as water generally flows into Blackwater Sound during fall, winter and early spring months, then out of the sound in late spring and summer. Low-frequency reversals occur over time scales of several days to about 2 wks throughout the study period. Flow into or out of Florida Bay typically averaged ±30–50 $m^3\ s^{-1}$ over these time scales. Low-frequency motions account for 80% of the total variance in along-channel volume transport. Harmonic analysis quantifies the amplitude of the dominant M_2 tidal constituent at 27 $m^3\ s^{-1}$and over half of any M_2 tidal cycle $380 \times 10^3\ m^3$ of water moves past the study site. Water level records indicate that the tidal transport is forced by Atlantic tides entering Barnes Sound through Biscayne Bay; Blackwater Sound is virtually tideless. Low-frequency flow through the channel is driven by a broad range of wind stress components acting to create water level differences between the two subbasins. Water level is most responsive to the 030–210° wind stress component and over all time scales between about 2 d and 4 wks this component of wind stress accounts for 50–85% of the total variance in water level differences between Barnes Sound and Blackwater Sound. These water level differences explain 88% of the variance in low-frequency flow through Jewfish Creek.

The circulation of water in and around Florida Bay transports a variety of dissolved and suspended material through the ecosystem. Some of these materials, originating from both natural and anthropogenic sources, are believed to be responsible for seagrass die-offs (Robblee et al., 1991; Thayer et al., 1994; Tomasko and Lapointe, 1994), widespread sponge mortality (Butler et al., 1995) and the decline of recreational gamefish populations (Tilmant, 1989). These findings have underlined the need for a better understanding of the bay's flow patterns to determine the source and pathway of environmental stressors being transported through the system.

Florida Bay's circulation is a complex response to forcing by tides, winds, and freshwater outflow. Of particular importance are the exchanges that occur between the bay and surrounding shallow water areas which help maintain or re-establish water quality in the bay by ridding it of pollutants and conserving brackish water conditions. Exchanges between Florida Bay and shelf waters of the Atlantic through tidal channels between Keys have been described by Smith (1994, in press). These studies have documented significant tidal exchanges through tidal channels as well as low-frequency flows commonly associated with meteorological forcing. Perhaps more importantly, Smith's work has shown a quasi-steady, long-term net outflow from Florida Bay through the major tidal channels in the Middle and Lower Keys which has been linked to a tidal pumping mechanism. Tidal waves entering Florida Bay from the Gulf of Mexico set-up water levels in the southeastern part of the bay which drives a bay-to-Atlantic flow through the channels

(Wang et al., 1994; Smith, pers. comm.). Long-term flow through the smaller channels in the Upper Keys is more variable.

Little is known about flow patterns in the interior of the bay. Pitts and Smith (1995) have described transport through three tidal channels that connect the western region of the bay with sub-basins in the interior. Their work showed that a long-term outflow from the bay through these channels is likely due to a local tidal pumping effect and that wind plays a relatively minor role in forcing water through these channels. Information from the central and relatively isolated northeastern section of the bay has been unavailable.

This paper describes the results of a 14-mo circulation study conducted in the northeastern corner of Florida Bay. The purpose of the study was to quantify the movement of water through Jewfish Creek, the main channel connecting the northeastern region of Florida Bay with Barnes Sound, a coastal lagoon that connects to Biscayne Bay and the Atlantic Ocean via Card Sound. The primary objectives of this paper are to characterize tidal and nontidal components of flow through Jewfish Creek, to establish long-term net flow patterns, and to quantify volume transport. Local wind and water level data are used to determine the relative importance of mechanisms forcing water between the two estuaries.

THE DATA

Current speed and directions were recorded near mid-channel just below mid depth in Jewfish Creek (25°11.19′N, 80°23.28′W) from 25 October 1995 to 12 December 1996 (Fig. 1). Average water depth at the study site was approximately 3.5 m; the channel width was 36 m. Currents were measured using a General Oceanics Mark-II current meter (accurate to ±1 cm s^{-1} and ±2°, respectively) suspended from a "gallows" type mooring. Currents were recorded hourly as vector averages of 4-sample bursts spaced at 2-s intervals.

Since calculations of volume transport require information on the rise and fall in water level, bottom pressure data were recorded at the study site with a Brancker Model TG-205 pressure recorder which has an accuracy of 0.02 db over a total pressure range of 0–20 db. Bottom pressures were recorded from 18 June to 11 December 1996.

Water level data from the two sub-basins connected by Jewfish Creek were obtained to investigate how tidal and low-frequency water level changes force water through the channel. Water levels recorded at Thursday Point in Barnes Sound (25°12.37′N, 80°22.50′W) were obtained from the South Florida Water Management District. Data were recorded hourly at a resolution of 0.3 cm from 25 October 1995 to 30 October 1996. Similar measurements from a study site in Blackwater Sound (25°10.15′N, 80°26.35′W) for the same time period were obtained from the National Park Service.

Wind data recorded at a NOAA C-MAN meteorological station on Molasses Reef (25°00.60′N, 80°22.80′W) were obtained from the National Data Buoy Center to investigate the relationship between water level variations and local wind stress. This weather station is located approximately 19 km southeast of the study site. C-MAN wind speeds and directions are recorded to the nearest 0.01 m s^{-1} and 1°, respectively. A 26-d gap in the wind data was filled using data from a C-MAN weather station located at Fowey Rocks (25°35.42′N, 80°05.80′W) 53 km northeast of the study site. A comparison of wind data from these weather stations over an 8-mo time period when both were in operation showed coherence above the 99.9% confidence level over all time scales longer than about a day.

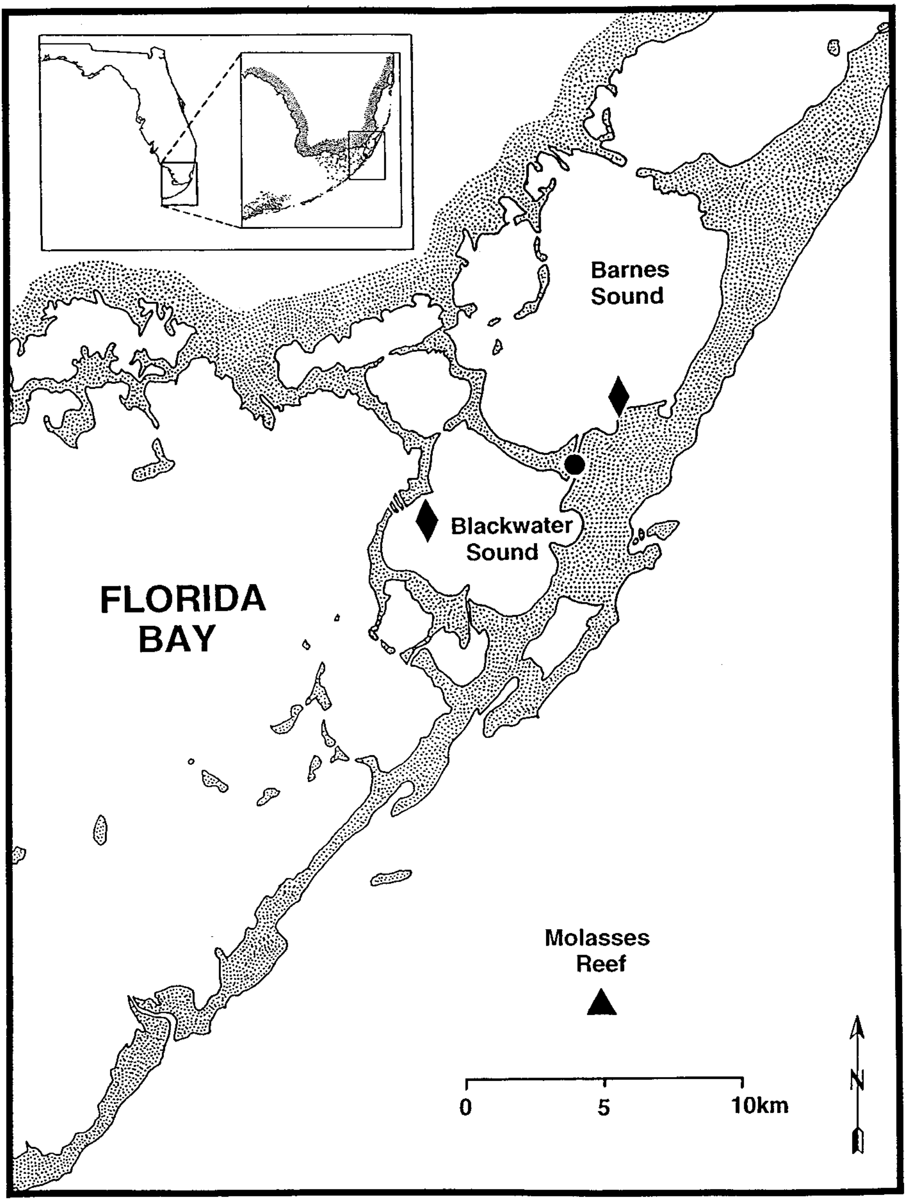

Figure 1. Map showing the study area in the upper Florida Keys. The circle shows the location of the study site in Jewfish Creek where currents and bottom pressures were recorded, diamonds represent the positions of the water level recorders in Barnes Sound and Blackwater Sound, and the triangle shows the location of the NOAA C-MAN weather station at Molasses Reef.

METHODOLOGY

Current vectors (speed and direction) were decomposed into along- 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. In this paper along-channel currents toward 191° (toward Blackwater Sound) are positive.

Volume transport calculations were made using the method described by Smith (in press). The channel was subdivided into two equal segments. Volume transport was calculated for each half, then summed to get the total for the cross-section. Flow meter data (Smith, 1994) indicate that in the protected waters of a tidal channel the vertical profile of along-channel current speed is logarithmic to a close approximation. The lateral variations in along-channel current speed were assumed to be parabolic. Surface measurements across the channel were obtained under both flood and ebb conditions to account for flood-dominant and ebb-dominant segments of the channel. Surface measurements from the mid-channel reference site and from one anchor station on each side of mid channel were obtained during a single tidal cycle. Surface currents at each anchor station were expressed as a fraction of the mid-channel value to define the parabola. Water depths used in the calculations were obtained by integrating closely spaced depth measurements with predicted tidal water level variations (see below). Depth measurements indicate a uniformly flat bottom and near-vertical sides.

To emphasize the long-term net movement of water past the study site the instantaneous volume transport values, in $m^3\ s^{-1}$, were multiplied by the 1-h time interval they represent, then summed and plotted as cumulative net volume transport. The low-frequency, nontidal variability in the hourly volume transport time series was obtained using a 40-h low-pass filter (Bloomfield, 1976) with a half-power point at approximately 37 h.

Harmonic constants of the principal tidal constituents for the volume transport, bottom pressures and water level data were quantified using either of two methods depending on the length of the time series. For the bottom pressure data, a 29-d harmonic analysis computer program (Dennis and Long, 1971) calculated the amplitude and phase angle of 24 tidal constituents. Since this time series was substantially longer than 29 d, several overlapping 29-d segments were used, and harmonic constants were vector averaged to obtain values more representative of the entire time series. For time series longer than 6 mo, which includes the volume transport and water level data, harmonic constants were quantified using the NOS least squares harmonic analysis program, “LSQHA” (Schureman, 1958). Given the amplitude from either approach, the total volume of water carried through the channel over each half tidal cycle by a given tidal constituent was quantified by dividing the product of the amplitude and period of that constituent by pi.

Amplitudes and phase angles of the principal tidal constituents for the bottom pressures recorded at the study site were input to a tidal prediction program based upon the technique described by Schureman (1958) to obtain a 414-d time series of predicted hourly water levels. The predicted water levels were then used in the volume transport calculations to simulate the tidal rise and fall in water level at the study site during the entire time period for which current meter data were available. The validity of using predicted water levels in the volume transport calculations was tested by comparing calculations made using the 176 d of bottom pressures recorded at the study site with those made using predicted values. A linear regression of the two volume transport time series revealed a high degree of similarity ($r = 0.998$). The standard error of the estimate, which is a measure of the scatter about the slope of the regression line, was determined to be $2.8\ m^3\ s^{-1}$.

The water level time series from Barnes Sound and Blackwater Sound were demeaned, low-pass filtered and plotted. The low-pass filtered water levels from Blackwater Sound were subtracted from the low-pass filtered Barnes Sound data, and differences were compared to low-pass filtered volume transport through Jewfish Creek to quantify the response to barotropic forcing.

Wind speeds and directions were converted to wind stress vectors using the algorithm recommended by Wu (1980). Spectral analysis (Little and Shure, 1988) was used to investigate the relationship between wind stress and water level fluctuations. Coherence spectra identified the 030–210° wind stress component as the one to which water level fluctuations were most responsive (Panofsky and Brier, 1958). Phase spectra indicated the time lag between wind stress forcing and the responding water level changes, while energy density and transfer function spectra provided the information needed to quantify the change in water level that occurs in response to a change in wind forcing.

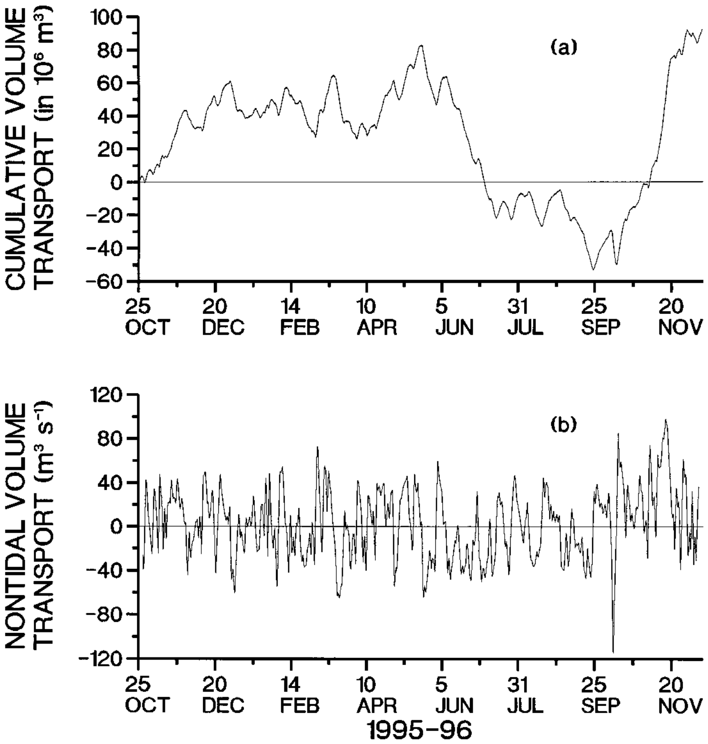

Figure 2. Cumulative volume transport (in 10^6 m^3, a) and low-pass filtered volume transport (in m^3 s^{-1}, b) through Jewfish Creek, 25 October 1995 to 12 December 1996. An ascending curve in the top plot and positive values in the bottom plot indicate transport into Blackwater Sound (toward 191°).

RESULTS

The cumulative net volume transport through Jewfish Creek from 25 October 1995 to 12 December 1996 is shown in Figure 2 (top plot). An ascending curve indicates a southward flow (191°) into Blackwater Sound. The plot is dominated by seasonal variations 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 the net transport into Blackwater Sound is approximately 82 million m^3 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 wks of the study and there is a strong inflow into Blackwater Sound of nearly 146 million m^3 of water, an average of 21.2 m^3 s^{-1}. Superimposed onto the seasonal signal are low-frequency reversals which occur over time scales of several days to about 2 wks throughout the 414-d study period. Flow into or out of Florida Bay typically averaged ±30–50 m^3 s^{-1}over these time scales.

Although impossible to see in the plot of this very long time series, tidal exchanges through Jewfish Creek are significant. The amplitude of the M_2 constituent is 26.7 m^3 s^{-1}. This trans-

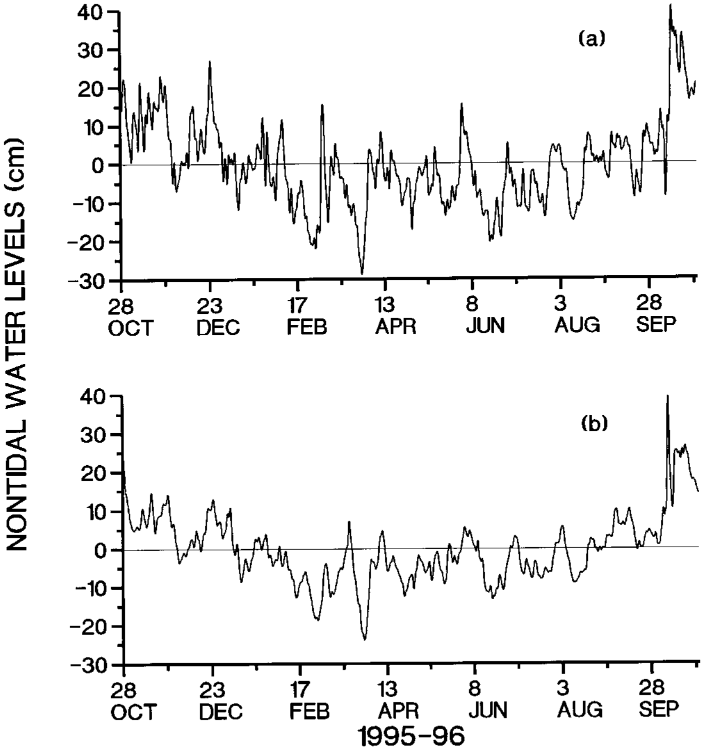

Figure 3. Low-pass filtered water levels (cm) from Barnes Sound (a) and from Blackwater Sound (b), 28 October 1995 to 27 October 1996.

Table 1. Harmonic constants of the principal tidal constituents for the along-channel currents, along-channel volume transport and bottom pressures recorded at the study site in Jewfish Creek and for water levels recorded in Barnes Sound and Blackwater Sound. Amplitudes (η) for currents, volume transport, pressure and water levels are in cm s^{-1}, m^3 s^{-1}, db and cm, respectively. Local phase angles (κ) are in degrees. The last row (Tidal transport) gives the volume of water, in 10^3 m^3, passing through the cross-section at the study site during each half tidal cycle.

		M_2	S_2	N_2	K_1	O_1	P_1
Along-channel	η	22.8	2.0	4.1	2.8	3.4	0.6
Currents	κ	026	052	002	272	312	275
Volume	η	26.7	2.7	5.1	3.4	4.1	0.8
Transport	κ	025	058	004	269	312	273
Pressure	η	3.5	0.8	0.7	1.0	0.5	0.3
	κ	025	304	359	064	179	064
Barnes Sound	η	5.7	0.7	1.0	0.9	1.0	0.2
Water levels	κ	041	084	029	300	329	305
Blackwater Sound	η	0.9	0.1	0.2	0.2	0.3	0.1
Water levels	κ	030	046	021	340	355	315
Tidal transport		380	37	74	93	121	22

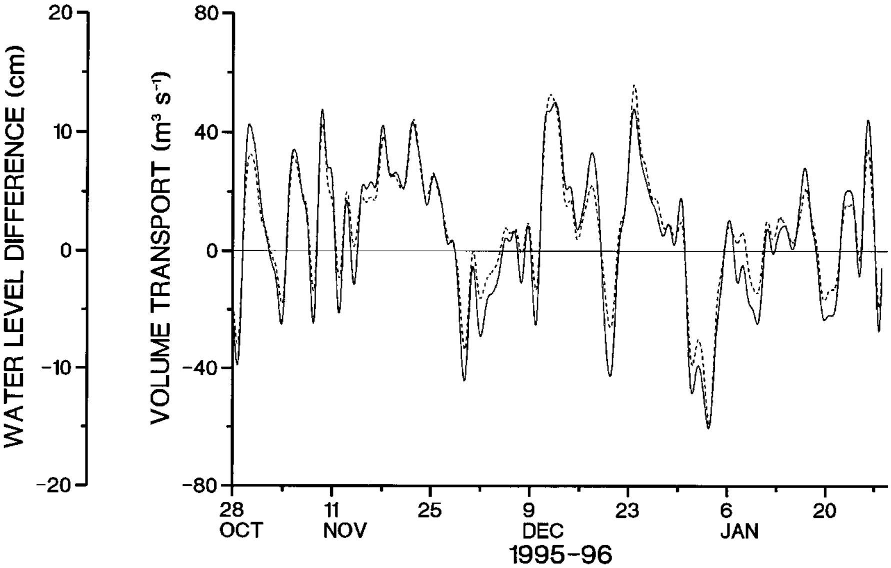

Figure 4. Low-pass filtered along-channel volume transport (m^3 s^{-1}) through Jewfish Creek (solid line) and the low-pass filtered water level difference (cm) between Barnes Sound and Blackwater Sound (dashed line), 28 October 1995 to 28 January 1996. Positive transport values indicate flow into Blackwater Sound (toward 191°) and Blackwater Sound water levels were subtracted from Barnes Sound water levels.

lates into a total volume transport of about 380×10^3 m^3 over any half M_2 tidal cycle. Amplitudes, phase angles and cumulative half tidal cycle transports for the principal diurnal and semidiurnal tidal constituents appear in Table 1. The interaction of the tidal rise and fall in water level with ebbs and floods through Jewfish Creek results in a tide-induced residual transport into Blackwater Sound that averages 0.79 m^3 s^{-1}. This is equivalent to 11.3×10^3 m^3 per M_2 tidal cycle, or about 3% of the total volume exchanged on a given tidal cycle.

The low-pass filtered volume transport is shown in the bottom plot of Figure 2. Transport rates generally range between ±30–50 m^3 s^{-1}. A maximum nontidal outflow from Blackwater Sound of 115 m^3 s^{-1} was recorded in early October while a maximum inflow of nearly 100 m^3 s^{-1} was recorded in mid November 1996. The standard deviation of the filtered along-channel components is 31 m^3 s^{-1}. These low-frequency motions account for nearly 80% of the total variance in the along-channel volume transport.

Figure 3 shows low-pass filtered water levels from Barnes Sound (top) and Blackwater Sound (bottom). Both time series exhibit a very low-frequency decrease then increase in water levels that reflect the seasonal sea level cycle (Smith, 1997). The annual (Sa) and semi-annual (Ssa) harmonics were quantified at 9.6 cm and 5.0 cm, respectively, for Barnes Sound, and 8.6 cm and 4.1 cm, respectively, for Blackwater Sound. Phase angles indicate that water levels in the two sub-basins rise and fall together over these very long time scales. Superimposed onto the annual rise and fall in water level are low-frequency fluctuations of 10–30 cm that occur over time scales of several days in both sub-basins. A close inspection reveals that while the two time series are generally in phase over these time scales there are time periods when they are 180° out of phase, most notable in early January and early October. The standard deviations of the low-pass filtered water levels

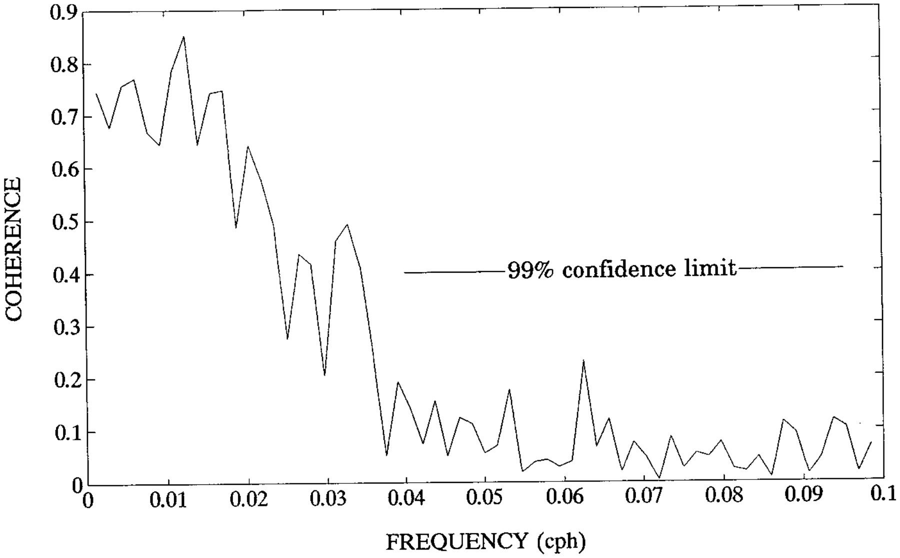

Figure 5. Coherence spectra of the low-pass filtered 030–210° component of wind stress and the low-pass filtered water level difference between Barnes Sound and Blackwater Sound.

recorded in Barnes Sound and Blackwater Sound are 10.9 cm and 8.8 cm, respectively. These nontidal fluctuations account for over 90% of the total variance in water level variations in both sounds. Note the greater variability in water level fluctuations that occurred in Barnes Sound.

Harmonic analysis of unfiltered water levels recorded in Blackwater Sound reveal a virtually tideless sub-basin. The M_2 amplitude was quantified at 0.9 cm while all other principal diurnal and semi-diurnal constituent amplitudes were either at or within the precision of the water level recorder (Table 1). Tidal water level fluctuations in Barnes Sound, while not large, are significantly greater than those recorded in Blackwater Sound. The M_2 amplitude is 5.7 cm.

To illustrate the cause-and-effect relationship between water level and flow through Jewfish Creek, the low-pass filtered volume transport (solid line) has been plotted together with the low-pass filtered water level difference between Barnes Sound and Blackwater Sound (dashed line) in Figure 4. Only the first 3 mo were plotted since using data from the entire 370-d overlap period would compress the curves to the extent that the relationship between the two variables would be obscured. The plot shows that the two time series are almost perfectly in phase. A correlation coefficient of 0.937 was calculated for the entire 1-yr overlap period, thus water level differences between the two sub-basins account for 88% of the variance in low-frequency volume transport through Jewfish Creek.

Spectral analysis indicates that a broad range of wind stress components are coherent with water level differences between the two sub-basins. Generally, winds from the northeast and southwest quadrants are coherent with water level differences over all time scales between about 2 d and 4 wks. Figure 5 shows the coherence spectrum calculated for water level difference and the 030°–210° wind stress component, the component to which water levels are most responsive. This component of wind stress is highly coherent with water level differences over all time scales between 2 and 27 d. Highest coherence (0.853, significant well above the 99.9% confidence level) occurs at a periodicity of 80 h. Phase spectra (not shown) indicate that at this periodicity the phase lead of wind stress is 30°, thus wind stress forcing has a time lead of about 7 h over water level changes. The magnitude of the transfer function indicates that a 1 dyne cm^{-2} wind stress out of the north, northeast (corresponding to an 8 m s^{-1} wind speed) produces an 8.7 cm water level difference between Barnes Sound and Blackwater Sound.

Spectral analysis of volume transport and water level difference indicates a coherence of 0.915 and a transfer function magnitude of 0.162 at the 80-h periodicity. Thus, a 1 m^3 s^{-1}volume transport through Jewfish Creek is produced by a 0.162 cm water level difference between Barnes Sound and Blackwater Sound. It follows, then, that an 8.7 cm water level difference between the two sub-basins, which results from a 1 dyne cm^{-2} wind stress from the north, northeast at the 80-hr periodicity, will produce a nontidal volume transport through Jewfish Creek of 54 m^3 s^{-1}.

Spectral analysis also indicates high coherence between winds from the northeast-southwest quadrants and water levels recorded in Barnes Sound at periodicities between 43 and 91 h (not shown). Again, highest coherence (0.738) occurred using the 030°–210° wind stress component at the 80-hr periodicity. Phase spectra show an approximately 6 hr time lead of wind stress over water level change at that periodicity. The transfer function spectra indicates that a 9.1 cm water level rise occurs at Thursday Point in response to a 1 dyne cm^{-2} wind stress out of the north, northeast. A comparison of winds and water levels recorded in Blackwater Sound revealed no statistically significant coherence over any time scale.

DISCUSSION

Results from this study document for the first time long-term transport through Jewfish Creek and, thereby, describe exchanges that occur between the northeastern section of Florida Bay and the Atlantic Ocean through Barnes Sound. These data provide new information regarding the relative importance of tide and wind forcing in explaining long-term net transport through Florida Bay.

The volume of water transported through Jewfish Creek by tidal processes is surprising given the isolation of the study area from shelf waters. Table 1 gives the total volume transport over any half M_2 tidal cycle as 380×10^3 m^3. For comparison, the volume of Blackwater Sound is approximately 72×10^6 m^3. Thus, M_2 tidal constituent exchanges through Jewfish Creek vary the volume of Blackwater Sound by about 0.5%. Calculations indicate that the residual tidal transport is relatively small—accounting for only 3% of the total volume exchanged on a given tidal cycle. This is significant, however, because it is a one-way transport process that does not depend upon tidal mixing, and it is a dependable baseline level of transport. But in Jewfish Creek it is a weak process. At a mean rate of 0.79 m^3 s^{-1} the tidal pumping mechanism will exchange approximately 0.09% of the volume of Blackwater Sound per day and nearly 3 yrs would be required to renew the volume of Blackwater Sound entirely.

Results indicate that the observed tidal exchanges through Jewfish Creek are driven by tidal water level fluctuations occurring in Barnes Sound. However, tidal water level variations in Barnes Sound are relatively small. Based on the dominant M_2 tidal constituent amplitude of 5.7 cm, the average semidiurnal tidal range in Barnes Sound is only 11.4 cm. This range is approximately 17% of the tidal range observed in the nearby shelf waters of the Atlantic (Martin, pers. comm.). Amplitudes in Barnes Sound are 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. Nevertheless, tidal water level changes in Barnes Sound are enough to force significant amounts of water through Jewfish Creek. By comparison, Blackwater Sound was found to be virtually tideless (Table 1). Apparently, tidal waves entering Florida Bay from the Gulf of Mexico never reach the northeast corner of the bay, having been filtered out by the bay's complex system of banks, sub-basins and narrow channels.

Nontidal transport through Jewfish Creek often dominates tidal exchanges. Statistics indicate that low-frequency processes account for nearly 80% of the total variance in along-channel volume transport. These nontidal processes exchange significant fractions of the volume in Blackwater Sound. For example, a 30 m^3 s^{-1} volume transport out of Blackwater Sound that is sustained for 2–3 d—which is fairly common in Jewfish Creek—would export a volume equivalent to 7–11% of the total volume in the sound. Thus, nontidal exchanges through Jewfish Creek provide an important flushing or water renewal mechanism for this relatively isolated sub-basin in northeastern Florida Bay.

The data presented here demonstrate that nontidal exchanges through Jewfish Creek are driven by low-frequency water level differences between Barnes Sound and Blackwater Sound and that these differences are closely coupled with local wind forcing over all time scales between 2 d and 4 wks. The greater response of water level variations to the 030°–210° wind stress component is likely due to the northeast-southwest orientation of Card Sound, Barnes Sound and Blackwater Sound. Prevailing winds during fall and winter months are primarily from the northeast quadrant and this orientation of inland water bodies would encourage transport from Barnes Sound into Blackwater Sound during those seasons. Prevailing winds from the southeast during the extended summer season would encourage transport out of Blackwater Sound. The seasonal signal observed in the long-term transport through Jewfish Creek reflects the seasonal wind shift for this region.

Spectral analysis indicates that water levels in Blackwater Sound and Barnes Sound respond quite differently to local wind stress. The probable explanation lies in the relative isolation of Blackwater Sound from shelf waters of the Atlantic Ocean and Gulf of Mexico. Water levels in Blackwater Sound are differentially damped and time-lagged relative to wind-driven set-ups or set-downs occurring in shelf waters. By comparison, Barnes Sound can more readily communicate with the Atlantic through Card Sound. The broad range of time scales for which water levels in Barnes Sound were coherent with wind stress suggests that water levels are responding to both local set-ups and set-downs within the lagoon system over the shorter time scales and synoptic-scale wind forcing of Atlantic shelf waters over intermediate and longer time scales.

Results from this study contribute to our understanding of Florida Bay circulation by extending into a previously unexplored section of the bay. Unlike the southeastern and western regions of the bay, where long-term flow through tidal channels appears to be forced primarily by tidal processes (Wang, et al., 1994; Pitts and Smith, 1995), flow through Jewfish Creek appears to be controlled primarily by wind-forced sea level slopes between adjoining basins and these winds have seasonal and intra-seasonal patterns. Tidal processes are significantly damped in this relatively isolated corner of the bay. These fundamental differences in how water moves through different sections of the estuary are important for understanding the dynamics of the bay's circulation. Results from this study, together with data from past and ongoing related studies, will contribute to the observational evidence needed to verify models of Florida Bay circulation.

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