Gulf of Mexico Science

Volume 20
Number 1 *Number 1*

Article 8

2002

Tidal and Wind-Driven Circulation through Lignum Vitae Basin, Florida Bay

Patrick A. Pitts
Harbor Branch Oceanographic Institution

DOI: 10.18785/goms.2001.08

Recommended Citation

Pitts, P. A. 2002. Tidal and Wind-Driven Circulation through Lignum Vitae Basin, Florida Bay. Gulf of Mexico Science 20 (1).
Retrieved from https://aquila.usm.edu/goms/vol20/iss1/8

Gulf of Mexico Science, 2002(1), pp. 75–85

Tidal and Wind-Driven Circulation through Lignum Vitae Basin, Florida Bay

PATRICK A. PITTS

Current meter time series collected between 1995 and 2001 are used to describe the exchanges of water through five tidal channels that connect Lignum Vitae Basin, a large subbasin in eastern Florida Bay, with adjacent subbasins and Atlantic shelf waters. Current data were combined with measured or simulated water levels, and channel geometry measurements were incorporated, to quantify volume transport through the channels. Results indicate a long-term inflow to Lignum Vitae Basin from the northwest through Gopher Keys Cut at an average rate of +11.9 m^3 s^{-1} during a 13-mo study period and from the west through South Twin Keys Cut at +9.6 m^3 s^{-1} during a 7-mo study period. A quasi-steady long-term outflow was observed to the east through Steamboat Channel, to the southeast through Indian Key Channel, and to the southwest through Bowlegs Cut. Outflow rates averaged −7.1, −25.8, and −6.5 m^3 s^{-1}, respectively, through these three channels. Interactions between tidal water–level fluctuations and ebbs or floods resulted in a tide-induced outflow from Lignum Vitae Basin through Gopher Keys and South Twin Keys cuts at rates of −0.06 and −0.09 m^3 s^{-1}, respectively. Tidal residual inflows of +5.8, +0.11, and +0.04 m^3 s^{-1} were calculated for Indian Key Channel, Steamboat Channel, and Bowlegs Cut, respectively. Comparisons of local winds with channel transport indicate that winds from any direction will force water through every channel except Steamboat Channel over most time scales greater than about 2 d. Flow through Steamboat Channel was coherent only with winds out of the northeast quadrant over time scales greater than about 1 d. Long-term flow was generally upwind through all channels except Bowlegs Cut.

Within the past decade a number of studies have documented the circulation of water in and around Florida Bay (Smith, 1994, 1998, 2000; Pitts, 1998; Wang, 1998). The stimulus for this work arose from concerns about reduced water quality in the bay, which may have contributed to the occurrence of widespread algae blooms and sponge mortality (Butler et al., 1995), seagrass dieoffs (Robblee et al., 1991; Thayer et al., 1994; Tomasko and Lapointe, 1994), and a decline in recreational gamefish populations (Tilmant, 1989). To determine where environmental stressors, like nutrients and suspended sediments, may be originating or transported, resource managers require information on flow patterns in and around the bay.

Most studies involving Florida Bay's circulation have examined the flow across the bay's western, southern, and eastern margins. Smith's (2000) work along the western boundary of the bay—taken to be the 81°05′W meridian—revealed a net movement of water into the bay across the northern and central sections of the boundary, whereas an outflow was observed across the southern section. Other studies by Smith (1994, 1998) have described the tidal and long-term net flow through virtually all of the major tidal channels between Keys that connect the bay with Atlantic shelf waters. With few exceptions, results showed a net movement of water out of Florida Bay and into the Atlantic. Only Snake Creek and Whale Harbor Channel, both relatively small channels in the Upper Keys, have shown a quasi-steady inflow to the bay.

Investigations of circulation in the interior of the bay include drifter and current meter studies. Wang (1998) tracked drogues moving northwest to southeast across the more open waters of western and southern Florida Bay. The time required to move through the bay was on the order of 5–10 d, depending on wind conditions at the time. Flow within the central and northern regions of the bay is very complex because of the topographic constraints imposed by shallow mud banks and mangrove islands. However, most current meter records from numerous channels connecting interior subbasins show a surprising degree of directional persistence, and most indicate an outflow from the interior (Pitts and Smith, 1995; Smith, unpubl. data). Pitts (1998) combined 14-mo current meter and water-level records to document the long-term volume transport through Jewfish Creek, the main channel

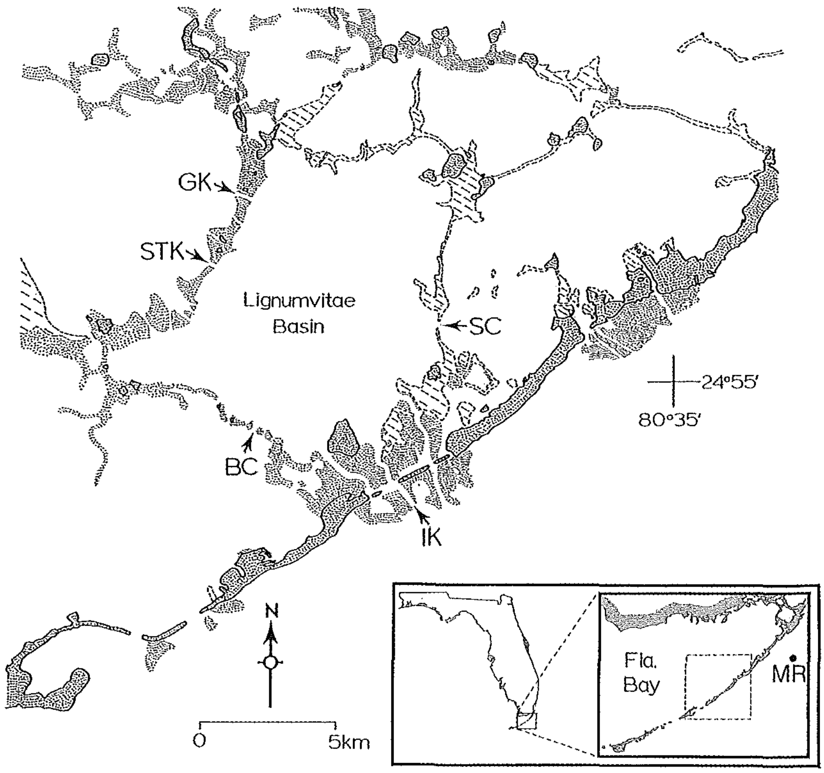

Fig. 1. Map showing study area. Arrows labeled GK, STK, BC, IK, and SC identify Gopher Keys Cut, South Twin Keys Cut, Bowlegs Cut, Indian Key Channel, and Steamboat Channel, respectively. Unbounded stippling indicates water depths of 0.5 m or less; hatching indicates shallow mud banks that may be exposed at low tide. The dot labeled MR on the inset map shows the location of the C-MAN station at Molasses Reef.

connecting Blackwater Sound in northeastern Florida Bay with Barnes Sound, a southern extension of Biscayne Bay. Results indicated well-defined seasonal fluctuations in flow through Jewfish Creek that were in response to seasonally changing wind stress. Water exits northeastern Florida Bay through this channel during late spring and summer and then enters from Barnes Sound the remainder of the year.

The purpose of this paper is to describe the flow of water into and out of Lignum Vitae Basin, a relatively large subbasin (87 km^2) on the eastern side of Florida Bay (Fig. 1). The primary objectives of the paper are to quantify tidal, low-frequency, and long-term volume transport through five primary channels that connect this subbasin with adjacent subbasins and Atlantic shelf waters. Local meteorological data are used to determine the role of wind forcing in driving exchanges between the subbasin and surrounding waters through these channels. Results contribute to our understanding of Florida Bay circulation and add to the database needed to validate model simulations.

DATA AND METHODS

Current measurements were made in mid-channel, at or just below middepth, in Gopher Keys Cut, South Twin Keys Cut, Steamboat Channel, Bowlegs Cut, and Indian Key Channel (Fig. 1). Water depths at the study sites averaged 5 m for Indian Key Channel, 3 m in Gopher Keys and South Twin Keys cuts, and approximately 2 m in the other two channels. Current speeds and directions were recorded in Bowlegs Cut and Steamboat Channel using a SeaPac Model 2000 electromagnetic current meter (accurate to <2 cm s^{-1} or 2% of signal strength and $\pm 0.5°$). General Oceanics Model 6011 inclinometers (accurate to ± 1 cm s^{-1} and $\pm 2°$) were used in the other three channels. Record lengths differ for each channel and range from 46 to 375 d. Data were recorded between July 1995 and June 2001.

Current vectors were decomposed into along- and across-channel components, but only the along-channel components were retained for analysis. Along-channel current components were defined as the headings at which the mean across-channel current component was minimal, while maintaining ebb and flood directions 180° apart. In this paper the along-channel flow into Lignum Vitae Basin through any channel is positive.

Because calculations of volume transport require information on the rise and fall in water level, bottom pressures were recorded hourly using a SeaData TDR-3 (±1.2-cm accuracy) in Indian Key Channel and Brancker TG-205s (±2.1-cm accuracy) in Gopher Keys and South Twin Keys cuts. Pressure data for Indian Key Channel were limited to a fraction of the current meter time series and were not available for the other two channels.

Volume transport calculations were made using the method described by Smith (1998). Indian Key Channel, by far the largest of the five, was subdivided into four equal segments. Volume transport was calculated for each segment and then summed to get the total for the entire channel. Lateral variations in surface current speed in Indian Key Channel were quantified using surface measurements obtained from a midchannel reference site and two sites on either side of the midchannel under both ebb and flood. Surface currents for each station were defined as a fraction of the midchannel value, and it was assumed that the surface current speed at any station remained a constant fraction of the midchannel speed throughout the ebb or flood phase of the tidal cycle. In the other four channels lateral variations in current speed were assumed to be parabolic, with the parabola defined by lateral variations in surface currents observed in a Florida Bay channel with similar geometric dimensions (Pitts, 1998). The vertical profile of along-channel current speed was assumed to be logarithmic (Smith, 1994). Depth measurements indicated relatively uniform bottoms for all channels except Indian Key Channel. Water depths used in the calculations were obtained by integrating closely spaced depth soundings with measured water levels (Gopher Keys and South Twin Keys cuts only) or predicted (Schureman, 1958) water-level variations added to the mean channel depth.

Harmonic constants of the principal diurnal and semidiurnal tidal constituents (M_2, S_2, N_2, K_1, and O_1) for the current meter, bottom pressure, and volume transport data were quantified using either of two methods depending on the length of the time series. For those time series longer than 6 mo, which include all data from Gopher Keys and South Twin Keys cuts and the current and volume transport time series from Indian Key Channel, harmonic constants were quantified using the least squares harmonic analysis approach (Schureman, 1958). Amplitudes and phase angles for time series less than 6-mo in length were calculated using a 29-d harmonic analysis program (Dennis and Long, 1971). Because most records were 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. Water-level tidal constituents for Bowlegs Cut and Steamboat Channel were obtained by interpolating contour plots of amplitudes and phase angles from Smith's (1997) study of Florida Bay tides.

Transport through all channels by tidal forcing alone was quantified by calculating volume transport using predicted ebbs and floods with the predicted tidal rise and fall in water level based on the five principal tidal constituents (Schureman, 1958). The total volume of water carried through the channel over each half-tidal cycle by a given tidal constituent was quantified by:

$$T = \frac{AP}{\pi}$$

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

The validity of using predicted water levels in the volume transport calculations was tested by comparing the calculations made using the bottom pressures recorded in Gopher Keys Cut with those made using predicted values for the same time period. A linear regression of the two transport time series using the entire 375-d records indicated a high degree of similarity ($r = 0.999$), and the endpoint of the accumulated transport time series using predicted water levels was only 0.03% less than the that of the accumulated time series using measured water levels. The standard error of the estimate (Hoel, 1976) was determined to be 0.18 $m^3\ s^{-1}$.

The validity of calculating volume transport for Bowlegs Cut and Steamboat Channel using predicted water levels generated from interpolated harmonic constants was also tested. Comparisons were made between transport calculations using predictions generated from artificially high or low amplitudes (±25% of the interpolated values) and phase angles (±15° from the interpolated values) for each constituent and those using the "best" interpolated values. Calculations for Bowlegs Cut indicate a reduction in accumulated transport of only 1% when amplitudes were 25% greater and phase angles lagged 15° behind the interpolated values; accumulated transport is increased to a maximum of only 0.7% when conditions are reversed. For Steamboat Channel, the maximum deviations of accumulated transport were −0.4% when amplitudes were increased by 25% and phase angles decreased 15°, and +0.3% under the opposite conditions. Additional details on volume transport calculations can be found in Smith (1998).

To characterize the long-term net movement of water through the channels, the instantaneous volume transport values (in $m^3 s^{-1}$) were multiplied by the 1-hr time interval they represent and then summed and plotted as cumulative net transport. Low-frequency, nontidal fluctuations in transport were determined by passing the hourly transport time series through a 40-hr low-pass filter that has a half-power point at approximately 37 hr (Bloomfield, 1976) and plotting the output.

Meteorological data recorded at NOAA's C-MAN station on Molasses Reef (25°0.60′N 80°22.80′W) were obtained through the National Data Buoy Center to investigate the relationship between wind stress and flow through the channels. Wind speeds, wind directions, air pressures, and air temperatures were recorded at accuracies of ± 1 m s^{-1}, $\pm 10°$, ± 1 hPa, and ± 1 C, respectively. All study sites are within 30–37 km southwest of the Molasses Reef C-MAN station (Fig. 1).

Wind speed and direction pairs were converted to wind stress vectors using the algorithm described by Wu (1980) for moderate wind speeds (1–20 m s^{-1}). Air pressures and air temperatures were used to quantify air density and were incorporated into the wind stress calculations. To describe seasonal variations in the local wind field, hourly wind stress vectors calculated from calendar year 1995 data were plotted head-to-tail as a progressive vector diagram. Spectral analysis (Little and Shure, 1988) was used to quantify the energy density, coherence, phase, and transfer function (gain) for wind stress and flow through the channels. To determine the wind stress components and periodicities for which channel flow was most responsive, coherence spectra were calculated at 15° intervals. Wind stress and volume transport components were low-pass filtered to isolate the low-frequency variations in transport associated with wind forcing, and filtered components were subsampled to improve temporal resolution over the longer time scales. Because of the abbreviated record from Steamboat Channel, no filtering or subsampling was performed on this time series before analysis. For all channels except Steamboat Channel, flow through the channel was significantly coherent (Panofsky and Brier, 1958) with a broad range of wind stress components. To quantify those wind stress components most effective in moving water through the channels, transfer function magnitudes were contour plotted on a periodicity–wind stress component grid.

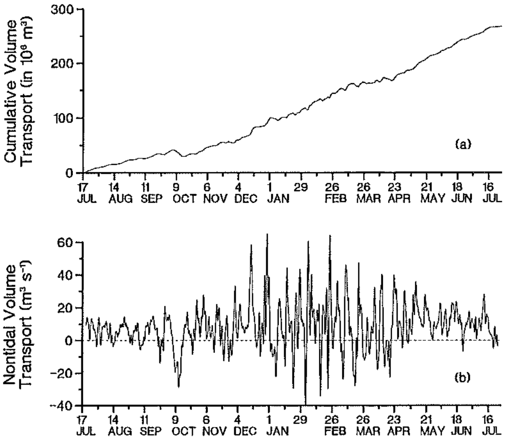

Fig. 2. Cumulative volume transport (a) and low-pass filtered along-channel transport (b) through Gopher Keys Cut from 17 July 1997 to 27 July 1998. Positive values indicate flow into Lignum Vitae Basin from the northwest.

RESULTS

Volume transport through channels.—The cumulative net volume transport through Gopher Keys Cut from July 17, 1998 to July 27, 1998 is shown in Figure 2a. An ascending curve indicates flow into Lignum Vitae Basin (toward 103°). The plot shows a long-term inflow that averaged 8.3 $m^3 s^{-1}$ during the 375-d study period (see Table 1 for comparisons with other channels). The plot also shows low-frequency reversals of inflow that lasted for several days to about a week. Significant reversals occurred during the fall, winter, and early spring months.

The low-pass filtered volume transport rates (Fig. 2b) were positive through most of the study period, accounting for the long-term inflow indicated by the cumulative transport plot. The magnitude of nontidal transport exhibited a very distinct seasonal pattern. Low-frequency fluctuations generally ranged between −5 and +15 $m^3 s^{-1}$ during the late spring and summer months. Fluctuations increased during the fall and early spring and ranged between −10 and +25 $m^3 s^{-1}$. Nontidal fluctuations were highest during the winter months and generally ranged between −30 and +60 $m^3 s^{-1}$. The standard deviation of the

TABLE 1. Channel geometry and flow calculations for the five study channels. The last three columns show mean volume transport (Transp.), residual tidal transport (Resid.), and the percent of the total variance in along-channel volume transport caused by the tides (Tid. Var.).

Channel	Study period	Width (m)	Area (m^2)	Speed (cm s^{-1})	Transp. (m^3 s^{-1})	Resid. (m^3 s^{-1})	Tid. Var. (%)
Gopher Keys Cut	17 July 1997 to 27 July 1998	34.6	76.4	+12.0	+8.3	−0.06	69
South Twin Keys Cut	29 Nov. 2000 to 27 June 2001	27.0	72.1	+14.2	+9.6	−0.09	67
Bowlegs Cut	27 Jan. to 10 June 1998	56.4	81.5	−8.5	−5.9	+0.11	69
Steamboat Channel	11 June to 27 July 1998	51.8	76.2	−9.8	−6.5	+0.04	74
Indian Key Channel	26 Oct. 1995 to 19 June 1996	100.0	528	−7.0	−25.8	+5.82	88

filtered along-channel transport for the entire study period was 13.5 m^3 s^{-1}.

Although not visible in the plots, tidal exchanges through Gopher Keys Cut were significant, accounting for nearly 70% of the total variance in volume transport through the channel. The amplitude of the dominant tidal constituent, the M_2 semidiurnal constituent, was 31.3 m^3 s^{-1}, which translates into a total volume transport of about 446 × 10^3 m^3 over any half M_2 tidal cycle. Amplitudes, phase angles, and half–tidal cycle transport volumes for the principal tidal constituents appear in Table 2. The interaction of the tidal rise and fall in water level with ebbs and floods through Gopher Keys Cut, using the five principal tidal constituents, resulted in a residual transport out of Lignum Vitae Basin that averaged −0.06 m^3 s^{-1}. This translates into a volume of 854 m^3 exiting the basin on a given M_2 tidal cycle or about 0.2% of the total volume exchanged over that cycle.

Results from South Twin Keys Cut showed a similar long-term pattern (Fig. 3a). The plot of cumulative volume transport indicates a long-term flow into Lignum Vitae Basin that averaged 9.6 m^3 s^{-1} from 29 Nov. 2000 to 27 June 2001. In addition to several short-lived reversals in long-term inflow, the plot shows two extended reversals. One of these occurred during the last 2 wk of Feb., whereas the other occurred from mid-April to mid-May. Low-frequency transport through this channel generally ranged between −20 and +50 m^3 s^{-1} (Fig. 3b). Like the flow through Gopher Keys Cut, nontidal transport fluctuations in South Twin Keys Cut were highest during the winter months. Seventy-four percent of the low-pass filtered transport values fall on the positive side of the plot through the 7-mo study period, accounting for the observed long-term inflow. The standard deviation of the filtered data was 18.0 m^3 s^{-1}. The residual tidal transport was toward the northwest or out of Lignum Vitae

TABLE 2. Harmonic constants of the principal tidal constituents for volume transport observed in each study channel: amplitudes (η) for volume transport (m^3 s^{-1}); local phase angles (κ) (deg.); and tidal transport (λ) (10^3 m^3), which gives the volume of water passing through the cross section at the study site during each half of the tidal cycle. Tidal transport through Indian Key Channel is in 10^6 m^3.

Channel		M_2	S_2	N_2	K_1	O_1
Gopher Keys Cut	η	31.3	5.8	5.0	8.8	9.4
	κ	118	155	088	104	100
	λ	446	79.8	72.6	241	278
South Twin Keys Cut	η	38.8	8.8	7.3	10.3	10.7
	κ	116	163	093	100	106
	λ	553	121	106	283	317
Bowlegs Cut	η	23.1	4.3	4.3	8.5	6.5
	κ	217	241	209	302	283
	λ	328	59.2	62.4	233	192
Steamboat Channel	η	12.9	1.0	2.2	1.3	2.4
	κ	255	240	237	305	291
	λ	184	13.8	31.9	35.7	71.0
Indian Key Channel	η	220	37.8	43.0	42.7	43.4
	κ	220	250	203	229	223
	λ	11.3	1.87	2.25	4.22	4.62

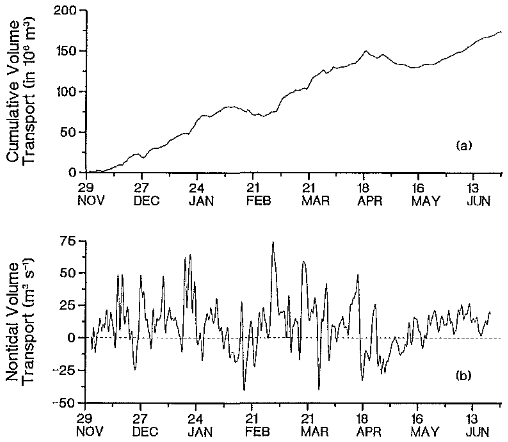

Fig. 3. Same data as in Figure 2 but for South Twin Keys Cut from 29 Nov. 2000 to 27 June 2001. Positive values indicate flow into Lignum Vitae Basin from the west.

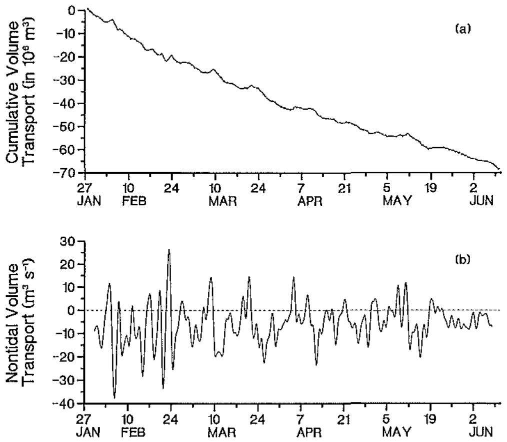

Fig. 4. Same data as in Figure 2 but for Bowlegs Cut from 27 Jan. to 10 June 1998. Negative values indicate an outflow from Lignum Vitae Basin to the southwest.

Basin (see Tables 1 and 2 for tidal transport values).

Data from the remaining three channels show a long-term outflow from Lignum Vitae Basin and a residual tidal transport into the subbasin (Table 1). Long-term outflow through Bowlegs Cut averaged -5.9 m^3 s^{-1} from 27 Jan. to 10 June 1998 (Fig. 4a). Reversals in outflow occurred throughout the record. The low-pass filtered time series (Fig. 4b) indicates fluctuations on the order of ± 25 m^3 s^{-1} during the midwinter months. These variations decreased to around ± 15 m^3 s^{-1} during the late winter and spring time period. The standard deviation of low-frequency, nontidal currents was 8.4 m^3 s^{-1}. Values in Figure 4b were negative through most of the study period, reflecting the long-term outflow observed in Figure 4a. Tables 1 and 2 give the values of tidal transport through Bowlegs Cut.

Figure 5a shows the cumulative volume transport through Steamboat Channel from 11 June to 27 July 1998. Water exited Lignum Vitae Basin at an average rate of -6.5 m^3 s^{-1} through this channel during the 46-d study period. The plot shows relatively little variation in long-term flow, which is consistent with flow characteristics of the other channels during the early summer season. Tidal oscillations in transport are easily visible in this relatively short time series. The low-pass filtered plot of transport through the channel (Fig. 5b) shows that the values fall almost exclusively on the negative side of the plot over the study period. Low-frequency flow generally ranged between -12 and -2 m^3 s^{-1}. The standard deviation in low-frequency transport was 3.5 m^3 s^{-1}. Harmonic analysis indicates that although tidal forcing dominated the instantaneous flow through this channel, tidal transport through Steamboat Channel was significantly weaker than through the other channels (Tables 1 and 2).

Figure 6a shows a long-term outflow from the subbasin and into the Atlantic through Indian Key Channel that averaged -25.8 m^3 s^{-1} from 26 Oct. 1995 to 19 June 1996. There appears to be a seasonal signal in the outflow, with stronger rates during the winter months and weaker rates during late fall and spring. Note the 6-wk time period in midspring when

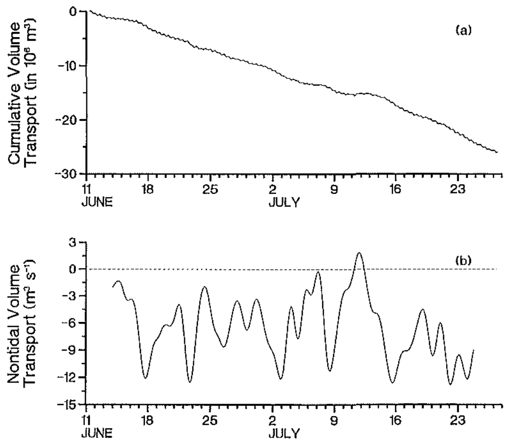

Fig. 5. Same data as in Figure 2 but for Steamboat Channel from 11 June to 27 July 1998. Negative values indicate an outflow from Lignum Vitae Basin to the east.

DOI: 10.18785/goms.2001.08

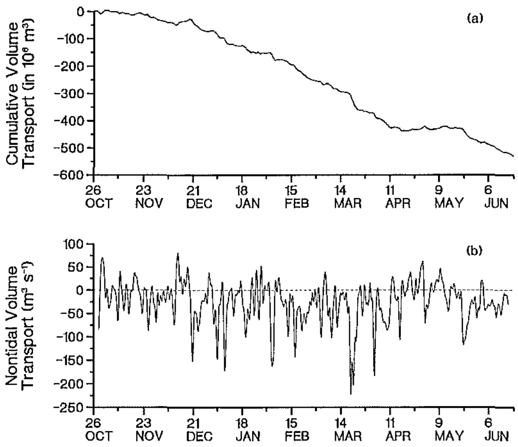

Fig. 6. Same data as in Figure 2 but for Indian Key Channel from 26 Oct. 1995 to 19 June 1996. Negative values indicate an outflow from Lignum Vitae Basin to the southeast.

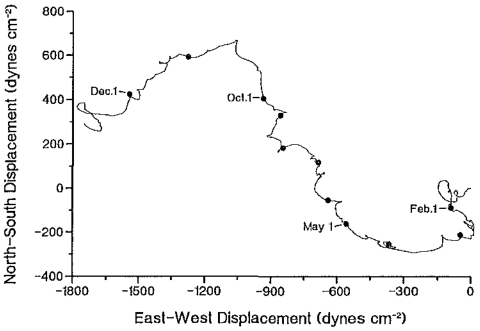

Fig. 7. Progressive vector diagram of wind stress recorded at Molasses Reef from 1 Jan. to 31 Dec. 1995. Dots occur at the first day of each month along the curve.

there was very little net movement through the channel. Low-frequency fluctuations generally ranged between -100 and $+50$ m^3 s^{-1} over this 237-d study period. The standard deviation of the low-pass filtered transport time series was 43 m^3 s^{-1}. Tidal forcing in Indian Key Channel accounted for 88% of the total variance in volume transport—the largest fraction of any of the study channels—which is not surprising given its direct connection with the Atlantic. Together with its larger cross-sectional area, this increased tidal forcing resulted in tidal constituent transport values that were an order of magnitude larger than for the other channels (Table 2). The tide-induced residual transport through Indian Key Channel was approximately two orders of magnitude larger than that of the other channels (Table 1).

To put the volumes exchanged through these channels in perspective, comparisons can be made with the total volume of water in Lignum Vitae Basin (approximately 152.6×10^6 m^3). For example, Indian Key Channel, by far the largest of the five study channels, exchanged approximately 2% of the volume of the subbasin over every M_2 tidal cycle. Using the mean outflow rate of -25.8 m^3 s^{-1} for Indian Key Channel, the time required to completely drain Lignum Vitae Basin would be 68 d, whereas the residual tidal transport alone ($+5.8$ m^3 s^{-1}) would require 305 d to completely replace the volume of the basin. By comparison, South Twin Keys Cut is the smallest of the study channels, and less than 0.4% of the subbasin's water was exchanged through this channel over an M_2 tidal cycle. The mean long-term inflow of 9.6 m^3 s^{-1} through this channel would require 184 d to fill the subbasin, and the tidal residual export of water at a rate of -0.09 m^3 s^{-1} would require nearly 54 yr to drain the subbasin.

Wind forcing.—Prevailing winds in this region are primarily from the eastern quadrant throughout the year (National Data Buoy Center, unpubl. data). During the fall and winter months there is a more southerly component, and during late spring and summer there is a more northerly component. Figure 7 provides an example of the annual wind pattern observed at Molasses Reef. The progressive vector diagram, constructed from data recorded from 1 Jan. through 31 Dec. 1995, shows large variations in wind direction from the beginning of January through March. The resultant wind direction was from the northeast during this time. Clockwise loops reflect cold fronts moving through the region. From early April through mid-Oct. the resultant wind stress was from the southeast. The characteristic fall shift in wind direction occurred in mid-Oct. of 1995, and for the remainder of the year the resultant wind stress was from the northeast.

With the exception of Steamboat Channel, spectral analysis indicates that transport through the channels was highly coherent with all 12 wind stress components over almost all time scales greater than about 1.5 d. Contour plots of gain values (Fig. 8) show which wind stress components were the most effective for forcing water through the channels. The top two plots show that the flow through Gopher Keys and South Twin Keys cuts responded to wind stress in a similar fashion. Note that the shorter record from South Twin Keys Cut resulted in poorer spectral resolution. Positive

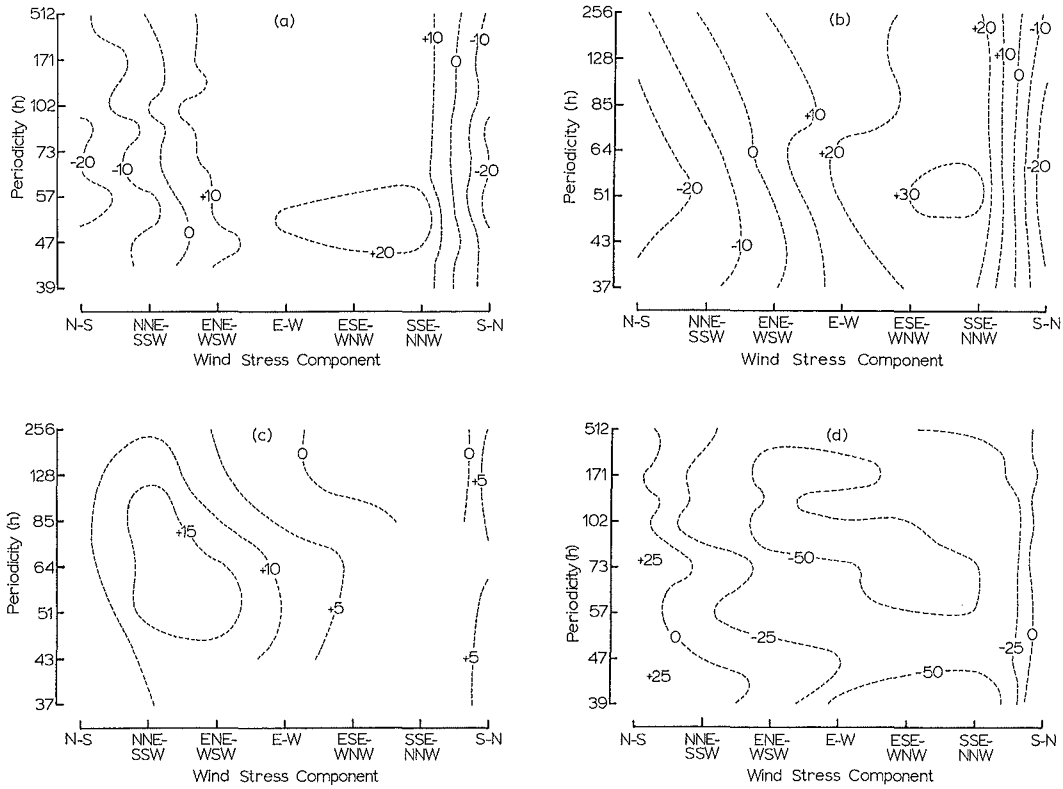

Fig. 8. Contour plots of the volume (in $m^3 s^{-1}$) transported through Gopher Keys Cut (a), South Twin Keys Cut (b), Bowlegs Cut (c), and Indian Key Channel (d) in response to a 1-dyne cm^{-2} wind stress. Each tick mark on the x-axis is labeled with two compass points that are 180° apart, signifying wind stress from either direction. Explanations of how to interpret the positive and negative gain values appear in the text.

values indicate flow into Lignum Vitae Basin through the channels when winds were from the WSW to NNW or out of the subbasin when winds were from the opposite directions. The plots indicate that winds from the south, ESE, and SSE were most effective for forcing water out of Lignum Vitae Basin through these two channels. For example, wind stress from the SSE reaching 1 dyne cm^{-2} will force as much as 32 m^3 of water per second out of the subbasin through South Twin Keys Cut over the 51-hr periodicity. Negative values indicate flow into the subbasin when winds were from the north or NNE; winds from the opposite directions forced an outflow from the subbasin. For example, a maximum of 27 $m^3 s^{-1}$ was forced into the basin through Gopher Keys Cut by a 1-dyne cm^{-2} wind stress from the north at the 57-hr periodicity.

Flow through Bowlegs Cut in response to the wind is shown in Figure 7c. Again, the shorter record from this channel resulted in poorer spectral resolution. Also, the lower right third of the plot is devoid of contour lines, indicating that coherence was not statistically significant for the ESE–WNW and SSE–NNW wind stress components over the 37–64 hr periodicities. Positive values indicate an outflow from the Lignum Vitae Basin for winds from the northeast quadrant. Negative values indicate an outflow when winds were from the NNW. The plot shows that transport through this channel was the most responsive to wind stress from the NNE and ENE over time scales ranging from 51 to 85 hr (2–4 d). A maximum outflow from Lignum Vitae Basin of nearly 19 $m^3 s^{-1}$ occurred through Bowlegs Cut in response to a 1-dyne cm^{-2} wind stress from the NNE at the 85-h periodicity.

Figure 7d shows the flow response in Indian Key Channel to wind stress. In this plot positive values indicate an outflow from the Lignum Vitae Basin when winds were from the north (over all time scales) or NNE (at periodicities of 39–43 hr) and an inflow when winds were from the south or SSE. Negative values indicate an inflow for all wind direction components from NNE to south (moving clockwise); winds from the opposite directions forced an outflow. The plot indicates that, with the exception of wind directly from the north, all wind directions out of the northeast or southeast quadrants forced water into Lignum Vitae Basin through this channel. Regions of strongest wind stress response include the ENE–WSW and east–west components acting over periodicities of 85–256 hr (3.5–10 d) and the ESE–WNW and SSE–NNW components over time scales of 37–43 and 57–85 hr, respectively. A maximum inflow or outflow of 67 $m^3 s^{-1}$ occurred for the ESE–WNW wind stress component over the 39-hr periodicity.

Spectral analysis results (not shown) indicate that flow through Steamboat Channel was significantly coherent only with winds out of the northeast quadrant over time scales between 43 and 128 hr. Phase and transfer function values indicate that flow through the channel was upwind. Highest coherence (0.639, significant above the 99.9% confidence level) occurred for the NNE–SSW wind stress component at a periodicity of 64 hr, which indicates that 64% of the total variance in along-channel volume transport through the channel can be attributed to this component of wind stress. The gain indicates that a peak of nearly 20 $m^3 s^{-1}$ of water was forced out of Lignum Vitae Basin through Steamboat Channel by a 1-dyne cm^{-2} wind stress from the NNE acting over a periodicity of 64 hr.

DISCUSSION

Results from the five study channels suggest that the circulation characteristics of Lignum Vitae Basin can be described as a roughly west-to-east flow-through system. Long-term volume transport patterns show a quasi-steady inflow to the subbasin from the northwest and west through Gopher Keys and South Twin Keys cuts, and an outflow to the southwest, southeast, and east through Bowlegs Cut, Indian Key Channel, and Steamboat Channel, respectively. This gulf-to-Atlantic flow pattern is similar to Florida Bay circulation as a whole, as documented by Smith (1994, 1998, 2000) and others (Lee et al., 1996; Wang, 1998).

The significance of the observed long-term pattern stems from environmental problems in Florida Bay and in the waters surrounding the Florida Keys. Some studies suggest that seagrass dieoffs observed in the interior of the bay may be related to an increase in anthropogenic nutrients flowing into the bay from the watershed (Lapointe, 1989; Tomasko and Lapointe, 1994). Other studies have linked Florida Bay seagrass mortality to infection by the marine slime mold *Labyrinthula* sp. (Robblee et al., 1991; Durako and Kuss, 1994). The data presented here indicate that Florida Bay water, along with whatever may be dissolved or suspended in it, is being transported to the eastern side of the bay and into Atlantic shelf waters where large seagrass meadows occur and where the continental United States' largest coral reef system is found. Thus, the observed outflow from the bay may introduce both nutrients and disease to the Atlantic side of the Keys. Some studies have already shown that Florida's coral reefs may be suffering from eutrophication processes caused by an increase in nutrient concentrations in waters surrounding the reefs (Lapointe and Clark, 1992; Lapointe and Matzie, 1996).

As has been observed in other tidal channel work in Florida Bay and the Florida Keys (Pitts and Smith, 1995; Pitts, 1998; Smith, 2002b), results from this study indicate that low-frequency nontidal transport is closely coupled with local wind stress. Depending on the time scale and channel of interest, the response of flow through the channels to wind stress, as quantified by spectral analysis, may or may not be easily explained. On the one hand, low-frequency flow over time scales of 1.5 d to 3 wk through all channels except Steamboat Channel is highly coherent with, and generally in the same direction as, wind stress. Winds from the northeastern, eastern, and southeastern sectors will set up shelf waters on the Atlantic side of the Keys, as well as on the western side of Lignum Vitae Basin, which forces water into the subbasin through Indian Key Channel and out of the subbasin through Gopher Keys, South Twin Keys, and Bowlegs cuts. Winds from the opposite directions reverse these setups and the corresponding flow through the channels.

On the other hand, the long-term flow through four of the five channels is toward the east or southeast—against the prevailing winds. Unpublished data from the National Data Buoy Center indicate that the prevailing winds in this region are from the northeast during the fall and winter months and from the east or southeast during the remainder of the year. Thus, prevailing winds should generally force water into Lignum Vitae Basin through Indian Key Channel most of the year, and they should force water out of the subbasin through Gopher Keys Cut and South Twin Keys Cut for most of the year. Although spectral analysis indicates that this is in fact the response through these channels over time scales of 1.5 d to 3 wk, the long-term flow is upwind. Also, it is unclear from this study what is driving the low-frequency (1.5- to 5-d periodicities) and long-term upwind flow through Steamboat Channel.

Smith (1994, 1998, 2002b) reported an upwind bay-to-Atlantic long-term flow through tidal channels between the Keys, and he as well as others (Wang et al., 1994) have suggested that residual tidal motions may be the cause. Tidal waves entering Florida Bay from the Gulf of Mexico set up water levels in the eastern and southeastern parts of the bay, which drives the observed bay-to-Atlantic flow. Another mechanism for forcing the long-term west-to-east flow in this area is the difference in mean sea level between the Gulf of Mexico and the adjacent waters of the Florida Straits. Chew (1982) documented a decrease of 8–9 cm in mean sea level between Key West and Miami, and Hetland et al. (1999) 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 more recent study by Lee and Smith (2002) indicates that sea level in western Florida Bay is about 6 cm higher than at Sombrero Reef, which is responsible for the long-term outflow observed through Long Key Channel, the main tidal channel connecting bay and shelf waters in the Middle Keys. The slope that drives the bay-to-Atlantic flow through Long Key Channel could also explain the west-to-east flow observed through Lignum Vitae Basin.

Considering its close proximity to the Atlantic, it was not surprising to find that tidal processes play an important role in driving water through the channels linking Lignum Vitae Basin with the surrounding waters. Tidal co-oscillations account for between 67 and 88% of the total variance in the observed volume transport through the channels. Although the rise and fall in water levels and the ebb and flood of currents through the channels interact to produce a residual tidal pumping into the subbasin through three of the five channels, this residual volume was only 0.5–1.3% of the volume moving through the channels by the M_2 constituent over any half tidal cycle. However, this residual tidal pumping represents a consistent and predictable source of water for Lignum Vitae Basin.

This study indicates that very long current meter time series (at least 6–8 mo in length) are desirable for providing the best indication of long-term mean conditions, and that shorter records, such as those obtained from Steamboat Channel and Bowlegs Cut, may inadequately represent long-term flow conditions. For example, both the 7-wk record from Steamboat Channel and the 34-wk time series from Indian Key Channel show an outflow from Lignum Vitae Basin. However, if one were to examine the transport through Indian Key Channel only during the 7-wk time period from mid-April to late May, one would see a slight inflow to the subbasin.

Volume transport values calculated for Indian Key Channel compare favorably with those found in an earlier study (Smith, 1998). A mean volume transport of -30.3 m^3 s^{-1} over an 84-d study period is about 17% more than the 25.8-m^3 s^{-1} mean transport value calculated in this study. The difference may be the result of the 6-wk time period in midspring of 1996 (this study) when there was little net movement of water through the channel, which significantly lowered the 8-mo mean. The 220-m^3 s^{-1} amplitude of the M_2 tidal constituent and the tide-induced residual transport into Florida Bay of 5.8 m^3 s^{-1} calculated for the present study are nearly identical to the earlier values. Also, it is noteworthy that the long-term transport through Teatable Channel, a smaller tidal channel located 1.5 km northeast of and parallel to Indian Key Channel, is out of Lignum Vitae Basin and into the Atlantic (Smith, 2002a).

Results from this study indicate that flow into and out of Lignum Vitae Basin, just one of Florida Bay's 26 subbasins, is quite complex, suggesting that the general circulation of the entire bay is very complex. Tidal forcing appears to play a dominant role in driving exchanges through the channels, accounting for 67–88% of the total variance in transport. The close proximity of Lignum Vitae Basin to the Atlantic undoubtedly accounts for the relative importance of tidal exchanges. Tidal forcing through subbasins in the interior of the bay is probably much weaker. Residual tidal transport forces water into Lignum Vitae Basin from the east, southeast, and southwest, and out of the subbasin to the west and northwest. Wind stress was shown to be closely linked with low-frequency exchanges through the channels. However, long-term transport was generally in the opposite direction of the prevailing winds, suggesting that the local circulation is embedded in a regional circulation that responds only secondarily to wind forcing.

ACKNOWLEDGMENTS

C. Humphrey, T. Moore, J. Absten, the Florida Institute of Oceanography, and the SEA-

KEYS Program are acknowledged for providing boat support and assistance in the field. I thank N. Smith for his assistance in deploying and recovering instrumentation and for his review of the manuscript. Wind data were acquired through the National Data Buoy Center at Stennis Space Center, MS. The study was funded in part by NOAA's South Florida Ecosystem Restoration Prediction and Modeling Program (Contract NA06OP0516). This is the Harbor Branch Oceanographic Institution, Inc., Contribution Number 1464.

LITERATURE CITED

BLOOMFIELD, P. 1976. Fourier analysis of time series: an introduction. John Wiley & Sons, New York.

BUTLER, M. J., IV, J. H. HUNT, W. F. HERNKIND, M. J. CHILDRESS, R. BERTELSEN, W. SHARP, T. MATTHEWS, J. M. FIELD, AND H. G. MARSHALL. 1995. Cascading disturbances in Florida Bay, USA; Cyanobacteria blooms, sponge mortality and implications for juvenile spiny lobsters *Panulirus argus*. Mar. Ecol. Prog. Ser. 129:119–125.

CHEW, F. 1982. The slope of the mean sea level along the Straits of Florida and its dynamical implications. Oceanol. Acta 5:21–30.

DENNIS, R. E., AND E. E. LONG. 1971. A user's guide to a computer program for harmonic analysis of data at tidal frequencies. NOAA Tech. Rep. 41, U.S. Dept. Comm., Rockville, MD.

DURAKO, M. J., AND K. M. KUSS. 1994. Effects of *Labyrinthula* infection on the photosynthetic capacity of *Thalassia testudinum*. Bull. Mar. Sci. 54:727–732.

HETLAND, R. D., Y. HSUEH, R. LEBEN, AND P. P. NIILER. 1999. A loop current-induced jet along the edge of the west Florida shelf. Geophys. Res. Lett. 26: 2239–2242.

HOEL, P. G. 1976. Elementary statistics. John Wiley & Sons, Inc., New York.

LAPOINTE, B. E. 1989. Macroalgal production and nutrient relations in oligotrophic areas of Florida Bay. Bull. Mar. Sci. 44:321–323.

LAPOINTE, B. E., AND M. CLARK. 1992. Nutrient inputs from the watershed and coastal eutrophication in the Florida Keys, U.S.A. Estuaries 15:465–476.

LAPOINTE, B. E., AND W. R. MATZIE. 1996. Effects of stormwater nutrient discharges on eutrophication processes in nearshore waters of the Florida Keys. Estuaries 19:422–435.

LEE, T. N., AND N. P. SMITH. 2002. Volume transport variability through the Florida Keys tidal channels. Cont. Shelf Res. In press.

LEE, T. N., E. WILLIAMS, AND N. P. SMITH. 1996. Flow within Florida Bay and interaction with surrounding waters, p. 48. *In:* Programs and abstracts, 1996 Florida Bay Science Conference, Florida Sea Grant, Key Largo, FL.

LITTLE, J., AND L. SHURE. 1988. Signal processing toolbox for use with MATLAB. The MathWorks, Inc., Natick, MA.

PANOFSKY, H. A., AND G. W. BRIER. 1958. Some applications of statistics to meteorology. The Pennsylvania State Univ., University Park, PA.

PITTS, P. A. 1998. Tidal and long-term volume transport through Jewfish Creek, Florida Keys. Bull. Mar. Sci. 63:559–570.

PITTS, P. A., AND N. P. SMITH. 1995. Long-term transport through three tidal channels in the interior of Florida Bay. Technical report in connection with Cooperative Agreement CA 5280-4-9022, National Park Service, Everglades Nat. Park, Homestead, FL.

ROBBLEE, M. B., T. R. BARBER, P. R. CARLSON JR., M. J. DURAKO, J. W. FOURQUREAN, L. K. MUEHLSTEIN, D. PORTER, L. A. YARBRO, R. T. ZIEMAN, AND J. C. ZIEMAN. 1991. Mass mortality of the tropical seagrass *Thalassia testudinum* in Florida Bay (USA). Mar. Ecol. Prog. Ser. 71:297–299.

SCHUREMAN, P. 1958. Manual of harmonic analysis and prediction of tides. Spec. Publ. 98, U.S. Dept. Comm., Govt. Printing Office, Washington, DC.

SMITH, N. P. 1994. Long-term Gulf-to-Atlantic transport through tidal channels in the Florida Keys. Bull. Mar. Sci. 54:602–609.

SMITH, N. P. 1997. An introduction to the tides of Florida Bay. Fla. Sci. 60:53–67.

SMITH, N. P. 1998. Tidal and long-term exchanges through channels in the middle and upper Florida Keys. Bull. Mar. Sci. 62:199–211.

SMITH, N. P. 2000. Observations of shallow-water transport and shear in western Florida Bay. J. Phys. Oceanogr. 30:1802–1808.

SMITH, N. P. 2002a. Florida Bay circulation studies. *In:* Recent research developments in geophysics. S. G. Pandalai (ed.). Kerala, India. In press.

SMITH, N. P. 2002b. Tidal, low-frequency and long-term mean transport through two channels in the Florida Keys. Cont. Shelf Res. In press.

THAYER, G. W., P. L. MURPHEY, AND M. W. LACROIX. 1994. Responses of plant communities in western Florida Bay to the die-off of seagrasses. Bull. Mar. Sci. 54:718–726.

TILMANT, J. T. 1989. A history and an overview of recent trends in the fisheries of Florida Bay. Bull. Mar. Sci. 44:3–22.

TOMASKO, D. A., AND B. E. LAPOINTE. 1994. An alternative hypothesis for the Florida Bay seagrass dieoff. Bull. Mar. Sci. 54:1086. [Abstract.]

WANG, J. D. 1998. Subtidal flow patterns in western Florida Bay. Estuar. Coast. Shelf Sci. 46:901–915.

WANG, J. D., J. VAN DE KREEKE, N. KRISHNAN, AND D. SMITH. 1994. Wind and tide response in Florida Bay. Bull. Mar. Sci. 54:579–601.

WU, J. 1980. Wind-stress coefficients over sea surface near neutral conditions—a revisit. J. Phys. Oceanogr. 10:727–740.

HARBOR BRANCH OCEANOGRAPHIC INSTITUTION, 5600 U.S. HIGHWAY 1 NORTH, FT. PIERCE, FLORIDA 34946. Date accepted: January 7, 2002.