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Volume transport variability through the Florida Keys tidal channels

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Abstract

Shipboard measurements of volume transports through the passages of the middle Florida Keys are used together with time series of moored transports, cross-Key sea level slopes and local wind records to investigate the mechanisms controlling transport variability. Predicted tidal transport amplitudes ranged from $\pm 6000\,m^3/s$ in Long Key Channel to $\pm 1500\,m^3/s$ in Channel 2. Subtidal transport variations are primarily due to local wind driven cross-Key sea level slopes. Subtidal transports through Long Key Channel ranged from $+1000\,m^3/s$ inflow to Florida Bay to $-2500\,m^3/s$ outflow to the reef tract. Wind directions oriented toward 190–315° will cause a positive cross-Key sea level slope and inflow to Florida Bay. All other wind directions will tend to cause a negative cross-Key slope of sea level and Gulf to Atlantic outflow toward the reef tract. Seasonal variation in local wind forcing results in maximum outflows from Florida Bay in the winter when increased winds toward the SE and S occur following cold front passages. Minimum outflow occurs in fall when winds toward the SW and W are more frequent and inflows to Florida Bay can persist for several days. The long-term mean flow is toward the southeast and the reef tract and is estimated at $-740\,m^3/s$ for the combined flows of the major channels in the middle Keys, with 7-Mile Bridge Channel accounting for about 50% of this flow, Long Key Channel carries about 35% of the flow and Channels 5 and 2 account for about 7% each. The mean Gulf to Atlantic flow is supported by sea level standing higher in western Florida Bay and the eastern Gulf than in the Keys Atlantic coastal zone. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Florida Keys; Volume transports; Sea level slopes

1. Introduction

The Gulf of Mexico is connected to the Atlantic through the Straits of Florida where a mean downstream slope of sea level helps to maintain the strong western boundary current system, the Loop Current/Florida Current that joins the two water bodies as an integral part of the North Atlantic subtropical gyre (Chew et al., 1982). The Gulf and Atlantic are also connected at the open passages between the Florida Keys (Fig. 1). Cross-Key sea level slopes from tidal and non-tidal processes will drive flows through these passages that can result in water exchange between the southwest Florida shelf, including western Florida Bay, and the Keys Atlantic coastal zone that encompasses the Florida Keys reef tract. Smith

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with each other through the tidal channels between the Keys and with strong offshore boundary currents at their outer edges; the Loop Current in the Gulf and Florida Current on the Atlantic side of the Keys. Loop Current eddies propagate southward along the outer edge of the wide west Florida shelf and develop into persistent eddy structures south of the Dry Tortugas that are forced downstream along the outer shelf and slope of the Keys (Paluszkiewicz et al., 1983; Lee et al., 1995; Fratantoni et al., 1998). The southwest Florida shelf is the southern extension of the wide, shallow west Florida shelf with its smoothly varying topography aligned in a northwest-southeast direction. Just north of the Keys the shallow inner shelf topography (depths <20 m) turns abruptly to the west to wrap around the western Keys, thus forming a shallow cul-de-sac in western Florida Bay. The west Florida shelf displays a strong coherent response to synoptic-scale alongshore wind forcing (Mitchum and Sturges, 1982; Mitchum and Clarke, 1986; Li and Weisberg, 1999; Weisberg et al., 2000) that is also observed in the inner shelf of southwest Florida (Lee et al., 2000). This response has all the characteristics of the arrested topographic wave response observed in the Middle Atlantic Bight (Csanady, 1982) and South Atlantic Bight (Lee et al., 1989). Synoptic-scale upwelling (downwelling) alongshore winds, together with the coastal constraint results in barotropic alongshore currents over the shelf aligned with the wind direction and balanced by a set-down (set-up) of coastal sea level. In addition, the west Florida shelf undergoes seasonal stratification of the water column from seasonal changes in wind mixing, air–sea exchange and river runoff along its eastern border (Weisberg et al., 1996). Fresh water runoff also occurs in the Ten Thousand Islands area through a series of small rivers, Shark River, Broad River and Lostmans River.

The Keys coastal zone consists of a narrow, curving shelf with complex topography (not shown in Fig. 1) associated with its shallow reef tract. The shoreline and adjacent coastal zone curves from a general north-south orientation in the upper Keys to an east-west alignment in the lower and western Keys (Fig. 1). Water depths vary from 0–3 m in the inner shelf to about 10 m in the Hawk Channel region of mid shelf, then decrease again to 0–5 m in the complex bathymetry of the reef tract, before the sudden steepening of the slope seaward of the shelf break at about 30 m. The curving shoreline causes regional differences in response to prevailing westward winds and Florida Current influences. The lower Keys are normally aligned with the wind and form a downwelling coast with onshore flow in the upper layer and offshore in the lower layer, and a westward coastal current that intensifies toward the west due to greater persistence of Florida Current eddies off the Tortugas (Lee and Williams, 1999). The prevailing westward wind is onshore in the upper Keys, with little influence on alongshore flow, whereas the Florida Current converges nearer the outer reefs in this region causing strong downstream flows with an onshore component in the upper layer and offshore in the lower layer. The outer shelf region of the Keys is dominated by meanders of the Florida Current and downstream propagation of frontal eddies that can cause energetic current reversals on time scales of days to weeks and significant cross-shelf transports (Lee et al., 1992, 1995; Fratantoni et al., 1998; Lee and Williams, 1999). The eddies decrease in size from 100 to 200 km off the Tortugas to tens of km in the middle and upper Keys, and increase in forward speed from 5–15 km/day off the western Keys to 15–30 km/day off the upper Keys, due to the narrowing of the Florida Straits channel as it curves to the north off the middle Keys (Lee et al., 1995). Currents in the mid shelf region of the Keys are mostly tide and wind forced. Subtidal currents in the lower and western Keys are persistent toward the west, whereas in the upper Keys there are seasonal reversals due to seasonal shifts in local winds (Lee, 1986; Pitts, 1994; Lee et al., 2000). Mean currents in the upper Keys are toward the north in summer when the winds are from a southeasterly direction, and shift to southward in the fall, winter and spring as the winds are mostly from the northeast and east. The Middle Keys represent a transition area for subtidal currents in the mid shelf region due to the change in wind alignment relative to the curving shoreline, and at the outer shelf due to the onshore convergence of the Florida Current, together with the rapid changes taking place in the configuration and speed of frontal eddies (Lee and Williams, 1999; Lee et al., 2000).

The largest passages connecting the southwest Florida shelf to the Keys coastal zone are found in the middle Keys (Fig. 1: Channel 5, Long Key Channel and Seven Mile Bridge) and western Keys (Northwest Channel and Rebecca Channel). Long Key Channel and Channel 5 connect western Florida Bay directly to the curving portion of the middle Keys coastal zone, whereas Seven Mile Bridge channel is located near the transition between the middle and lower Keys subregions. Rebecca Channel connects the western Keys Atlantic coastal waters to the southwest Florida shelf, as does the Northwest Channel at Key West. Smith (1994 and 1998) has used current meters and bottom pressure recorders placed within the Keys passages to estimate cumulative flow displacements and volume transports. He shows that when measurements extend over several months or longer there is a persistent Gulf to Atlantic mean flow through all the larger passages in the middle Keys, whereas long-term flows through the upper Keys passages are weak in comparison and generally in the direction of Florida Bay. For Long Key Channel, Smith estimated a mean outflow to the Keys of $-262\,\mathrm{m^3/s}$ for a 1 year period from summer 1992 to 1993, with strongest transport toward the Keys in winter and spring months. Over shorter periods of several days to weeks the mean flow can reverse and flow into Florida Bay with high correlation to local winds (Smith and Lee, submitted for publication).

3. Methods

As part of the SFERPM Program we have made direct measurements of volume transports in the major passages of the middle Keys over semi-diurnal tidal periods using a RDI 600 kHz shipboard ADCP with 20° beam angle. Transects were made perpendicular to the passages on six occasions at Long Key Channel, Channel 5 and Channel 2 and on a single day at 7-Mile Bridge. The instrument was mounted forward of the bow between the hulls of a shallow catamaran to avoid any hull distortions of the current field. Transects were made every 1–2 h over a semi-diurnal tidal cycle. Channels 2 and 5 were profiled consecutively on a single day and Long Key Channel on a second day. It took approximately 5, 10 and 25 min to complete transects at Channels 2, 5 and Long Key, respectively. The Seven Mile Bridge transect took approximately 1 h.

To investigate cross-Key sea level slopes as a cause for low-frequency volume transport fluctuations we installed Seabird bottom pressure recorders on current meter moorings in western Florida Bay north of Long Key Channel and in the Keys coastal zone offshore of Tennessee Reef (Fig. 1). These instruments can resolve sea level changes to an accuracy of about ± 1 cm. Wind data are obtained from nearby CMAN stations at Sombrero and Molasses Reefs and north of Long Key and adjusted for a uniform 10 m height using: $W_{10} = W_z(10/z)^{0.1}$, where W is the wind speed at height, z, above the sea surface. Wind stress vector τ is computed from: $\tau = \rho_a C_D U_{10}|U_{10}|$, where ρ_a is the density of air, C_D is a constant drag coefficient equal to 1.5×10^{-3} and U_{10} is the wind vector at the 10 m height. Winds have been shown to be highly coherent at stations throughout the Keys and Florida Bay on time scales longer than 1 day (Lee and Williams, 1999; Smith unpublished observations). Station locations are shown in Fig. 1. Station positions and instrument depths are given in Table 1. All time series data are filtered with a 40-h low-pass Lancos filter to remove tidal, sea breeze and inertial fluctuations so that low-frequency variations can be better observed. In addition, bottom pressure records are demeaned and detrended to remove differences due to different water depths at the measurement sites and to remove any long-term drift in the sensors.

4. Results

4.1. Shipboard transports

Shipboard derived volume transports through Channels 2, 5 and Long Key are shown in Fig. 2a and b for winter and summer examples. Shipboard

Table 1
Station locations and deployment dates

Station	Instrument	Deployment dates	Latitude N	Longitude W	Depth (m)
WFB	SeaCat P/C/T	9/21/97–4/1/98	24°55.8′	81°05.6′	4
Tenn.	SeaCat P/C/T	9/20/97–5/4/98	24°44.4′	80°46.7′	26

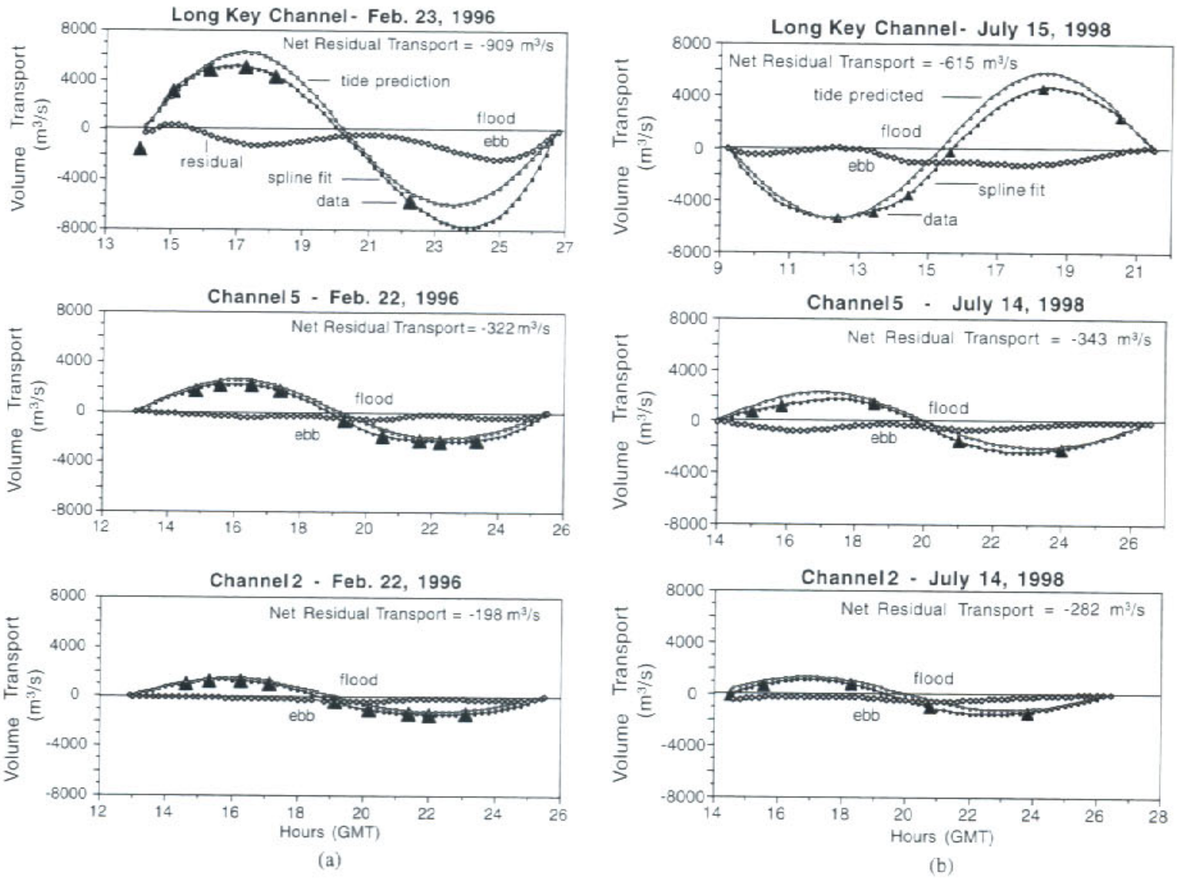

Fig. 2. (a) Shipboard ADCP derived volume transports for Channels 5, 2 and Long Key Channel on February 22 and 23, 1996. Included are the measured transports (solid triangles), spline fit to measured transports (small solid circles), tide predicted transports (small open squares) and residual transports (open squares). (b) Shipboard ADCP derived volume transports for Channels 5, 2 and Long Key Channel on July 14 and 15, 1998. Included are the measured transports (solid triangles), spline fit to measured transports (small solid circles), tide predicted transports (small open squares) and residual transports (open squares).

transports are shown with solid triangles. These data are fitted with a cubic spline to interpolate transports every 12 min. Positive values are toward Florida Bay and negative values are toward the reef tract. Also shown are the tidal predicted transports derived from tidal predicted sea level and current variations using the method of Smith and Lee (submitted for publication), and residual transports computed as spline fit transports minus tidal predicted. Fig. 2 clearly shows the relative magnitude differences between the three flow channels. Amplitudes of tidal predicted transports are generally about $\pm 6000\,m^3/s$ at Long Key, $\pm 2500\,m^3/s$ at Channel 5 and $\pm 1500\,m^3/s$ at Channel 2. However, these amplitudes can vary by as much as $1000\,m^3/s$ and are also usually unequal for the flood and ebb stages.

Measured transports in all three channels indicate a significant net transport out of Florida Bay toward the reef tract. This is seen in both the longer durations of the ebb cycle and greater magnitudes of the ebb flows. Because our shipboard measurements only extend over a semi-diurnal period it is quite likely that unresolved diurnal tidal constituents can cause aliasing from the diurnal tidal inequality that would contribute to the observed net outflow. To account for this, we remove the tidal predicted volume transports from the observed transports for each channel to form residual transport time series. The average of the residual transport time series over the semi-diurnal tidal cycle is the net residual transport.

Table 2 lists the net transports for each section. At times the net tidal transport can be large either toward Florida Bay or the reef tract. This is not a true tidal residual transport, but rather is an artifact caused by aliasing from the diurnal tidal inequality. Smith and Lee (submitted for publication) have shown that the semi-diurnal tidal constituent (M_2) has a rather small net residual transport into Florida Bay of 160, 127 and $68\,m^3/s$ in Channels 5, 2 and Long Key, respectively. This indicates that aliasing from the diurnal inequality can be a major source of uncertainty in our shipboard derived net transports and must be corrected for as shown in Table 2 and Fig. 2 to

Table 2
Volume transports, Q (m^3/s), derived from shipboard ADCP sections across tidal channels in the Middle Keys with and without correction for tidal diurnal inequality

Date	Channel	Net observed Q	Net tidal inequality Q	Net residual Q
2/23/96	Long Key	−987	−78	−909
2/22/96	Channel 5	−230	92	−322
2/22/96	Channel 2	−174	15	−189
	Total	−1391	29	−1420
6/16/96	Long Key	−1379	−884	−495
6/15/96	Channel 5	−110	−191	81
6/15/96	Channel 2	−177	−137	−40
	Total	−1666	−1212	−454
10/24/96	Long Key	−50	440	−390
10/23/96	Channel 5	−52	96	−148
10/23/96	Channel 2	−83	50	−133
	Total	−85	586	−671
2/27/97	Long Key	−346	−206	−140
2/26/97	Channel 5	286	20	266
2/26/97	Channel 2	144	−1	145
	Total	84	−187	271
5/20/97	Long Key	−993	−323	−670
5/21/97	Channel 5	−356	−156	−200
5/21/97	Channel 2	−280	−110	−170
	Total	−1629	−589	−1040
7/15/98	Long Key	−541	74	−615
7/14/98	Channel 5	−344	−1	−343
7/14/98	Channel 2	−306	−24	−282
	Total	−1191	49	−1240

obtain the residual transports from low-frequency processes. After correction, our residual transports were found to be toward the reef tract for 5 out of the 6 measurement periods, with combined flows from the three channels ranging from about –450 to $-1420\,m^3/s$. The net outflow from Long Key Channel was generally 2–3 times larger than that from Channels 5 and 2, which were about equal. On February 26, 1997 the combined net flow was toward Florida Bay at $+270\,m^3/s$. Low-frequency reversals of flow direction in these channels have been previously shown by Smith (1994), with strong visual similarity to variations in local winds (Smith and Lee, submitted for publication).

4.2. Cross-Key sea level slopes and volume transports

Time series measurements of cross-Key sea level difference (SLD) between western Florida Bay and the Keys Atlantic coastal waters were made from recorded bottom pressure variations at moorings WFB and Tennessee Reef (Tenn.) over a 192 day period from September 21, 1997 to April 1, 1998 (see Fig. 1 for locations). Low-frequency SLD time series are determined by first demeaning and detrending the bottom pressure measurements and then taking the pressure difference between Tenn. and WFB sites. Subtidal time series of sea level variations at WFB and Tenn. stations are plotted in Fig. 3 together with the cross-Key SLD. Long Key Channel volume transport and Sombrero Reef CMAN wind stress components are also shown on this figure. The volume transport time series were derived from current meter and sea level data for a 279 day period from October 21, 1997 to July 27, 1998 using the method of Smith and Lee (submitted for publication). The sea level difference and volume transport time series have been normalized by their standard deviations for better visual comparison. Also the mean cross-Key SLD as determined from

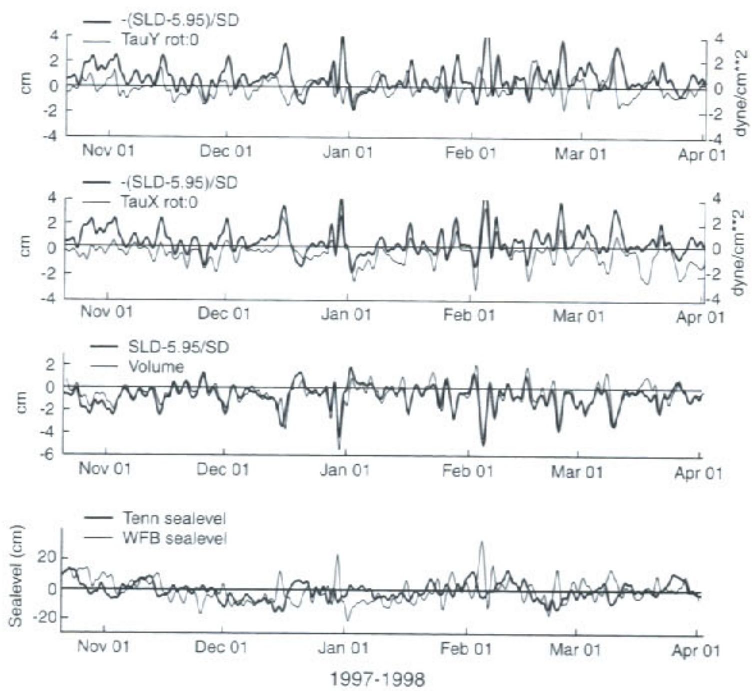

Fig. 3. Subtidal times series of demeaned and detrended sea level height at Tenn. and WFB sites (lower panel); sea level difference (SLD: Tenn.−WFB) plus the mean SLD (−5.95 cm) divided by the standard deviation (SD) and volume transport through Long Key Channel (+ is toward Florida Bay) (middle panel); and east-west wind stress (TauX) plotted with the negative of the SLD (upper panel) for October 1997–April 1998.

regression with volume transport (discussed below) has been added to the SLD time series to further highlight the agreement between the two separately derived data sets.

Amplitudes of sea level variations are about ± 10 cm at Tenn. and reach ± 20 cm in western Florida Bay (Fig. 3). Low-frequency sea level variations at WFB and Tenn. stations tend to be out of phase for periods less than 2 weeks over most of the measurement period. The combination of the out of phase relationship in sea level and greater amplitude of the variations in western Florida Bay results in a fluctuating slope of sea level across the Keys. Comparing the normalized SLD time series to the normalized volume transport time series by dividing by their standard deviations (SD = 487 m^3/s for transport and 8.6 cm for SLD) shows clearly that the low-frequency transport variations through Long Key Channel are driven by the changes in cross-Key sea level slopes (Fig. 3). A near-linear relationship exists between sea level difference and volume transport as shown in Fig. 4. Changes in sea level difference account for about 73% of the volume transport variance. A sea level difference of 10 cm can drive a volume transport of approximately 480 m^3/s. Similarly, comparison of east-west wind stress component time series to SLD indicates that these

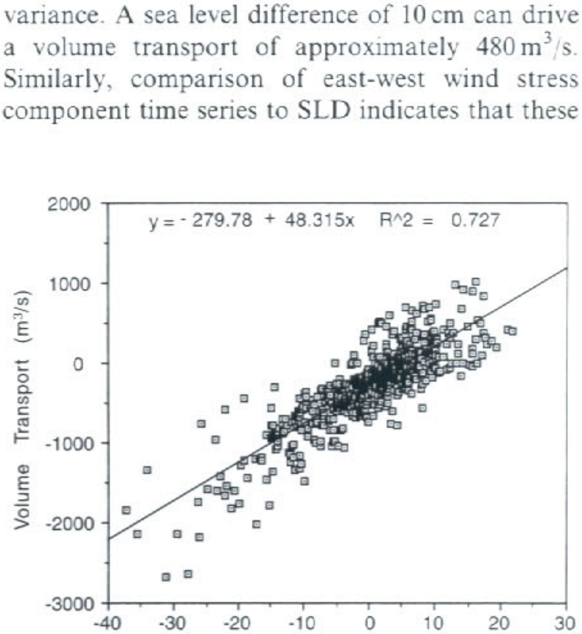

Fig. 4. Linear fit of volume transport through Long Key Channel versus SLD (Tenn.–WFB) for the data shown in Fig. 3, October 1997–April 1998.

slope variations are highly coherent with local wind forcing. Fig. 4 also shows a mean bias of $-280\,m^3$/s in transport that represents the mean background transport from western Florida Bay to the reef tract during this period. Applying the linear relationship of Fig. 4 to the mean flow requires a mean sea level slope of -5.95 cm, indicating that mean sea level stands about 6 cm higher in western Florida Bay than in the Atlantic side of the Keys. Mean sea level slopes cannot be determined directly from pairs of bottom pressure measurements without leveling the stations, which is not practical for bottom pressure recorders. Therefore, the mean sea level slope derived from regression analysis was added to the sea level difference fluctuation time series in Fig. 3 to account for the observed mean transport through Long Key Channel.

5. Discussion

5.1. Cross-Key sea level slopes

In the open ocean gravitational forces associated with sea level slopes generate surface currents, v_s, that are in geostrophic balance with the horizontal pressure gradient according to: $v_s f = g\delta\eta / L$, where $\delta\eta$ is the sea level difference over the width of the current, L. On a continental shelf the "coastal constraint" of no-flow into or out of the coastal boundary causes an "adjustment drift" of barotropic cross-shelf flow in response to alongshore wind forcing that accelerates an alongshore barotropic flow (Csanady, 1982). Geostrophic adjustment then causes the cross-shelf sea level slope to balance the alongshore flow, resulting in either set-up or set-down of coastal sea level depending on whether the wind forcing is either downwelling or upwelling favorable, respectively. A cross-shelf wind will result in a simple wind forced set-up or set-down of sea level according to whether the wind is onshore or offshore, respectively, without the dynamical adjustment caused by an alongshore current.

The Florida Keys separates two physically different coastal regimes. The southwest Florida shelf adjacent to the Keys is extremely shallow (depths <10 m: Fig. 1) and tends to form a concave shaped cul-de-sac in western Florida Bay that opens to the west. With this configuration sea level in western Florida Bay is highly responsive to local east-west winds. Thus low-frequency sea level variations in western Florida Bay are strongly coherent with the east-west component of wind stress at Sombrero in the 2–10 day period band of higher wind energy (Fig. 5). The much larger west Florida shelf is aligned in a NNW–SSE direction and is highly responsive to alongshore winds (Mitchum and Sturges, 1982; Weisberg et al., 1996; Li and Weisberg, 1999; Weisberg et al., 2000; Lee et al., 2000). The resulting geostrophic adjustments of sea level to alongshore shelf flows can also influence sea level in the southern part of the west Florida shelf. Therefore, sea level in western Florida Bay can be set-up in response to northward winds that are downwelling favorable on the west Florida shelf, as well as sea level set-down to southward (upwelling) winds on the west Florida shelf. Fig. 3 shows that these effects combine to generally produce a rise of sea level at WFB station for winds toward the north, northeast, east and southeast, and lowering of sea level for winds toward the south, southwest, west and northwest. In addition, water levels on the west Florida shelf and western Florida Bay can be affected by long-period variations of the position of the Loop Current (Sturges and Evans, 1983; Lee et al., 2000).

The Atlantic coastal zone of the Keys consists of a narrow curving shelf with depths <10 m that is responsive to alongshore wind forcing in the formation of alongshore flows with compensating sea level adjustment (Lee and Williams, 1999). The middle Keys coastal zone is aligned in a NE–SW direction and coastal sea level will rise (fall) in response to downwelling (upwelling) winds, as well

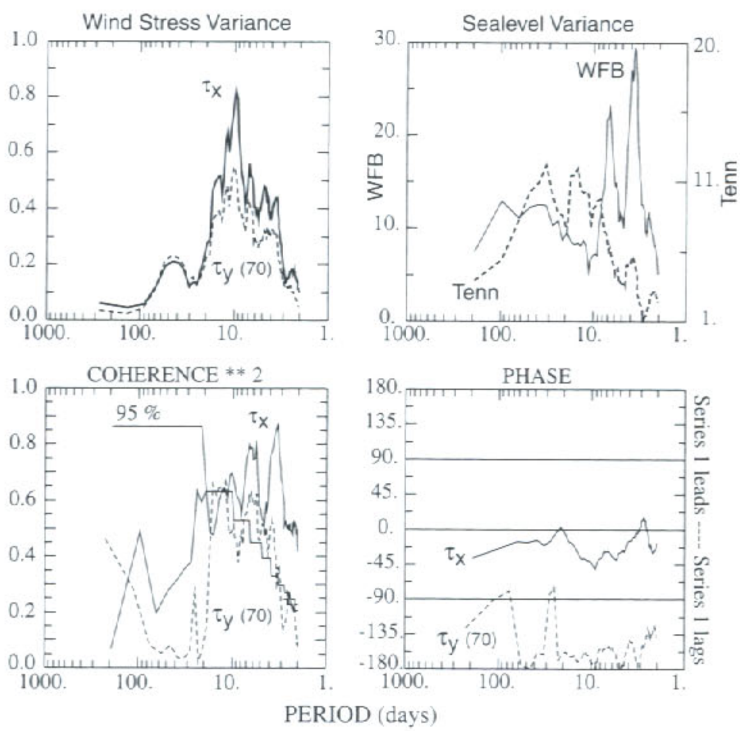

Fig. 5. Spectra, coherence and phase between the east-west component of Sombrero wind stress and sea level at WFB and between alongshore wind stress (τ_y rotated 70°) and sea level at Tenn. (dashed line) for September 1997–April 1998 period using 40-h low-pass filtered data.

as onshore (offshore) winds. Coherence estimates between low-frequency sea level variations at the Tenn. station and alongshore winds rotated in 10° intervals show highest coherence with winds toward 230–250° (or 50–70°), which combines influences from both alongshore and cross-shore wind forcing in this region (Fig. 5).

Fig. 3 shows that sea level variations at Tenn. and WFB sites tend to be out of phase for periods less than 2 weeks, thus causing a sea level slope across the Keys. Magnitude of the SLD ranged from −40 to +15 cm (when multiplied by standard deviation of 8.6 cm). This out of phase relationship arises due to the different responses at these sites to the same wind stress, as discussed above. Fig. 6 shows the orientation of the two shelf regimes and indicates that wind directions toward the southwest to west will cause a set-down of sea level in western Florida Bay and a set-up along the Keys, thus forming a positive sea level slope across the Keys and flow into Florida Bay (Fig. 3). A wind toward the northwest will be downwelling favorable on the west Florida shelf and cause a set-up of sea level along the coast and in western Florida Bay. This same wind is onshore in the middle Keys

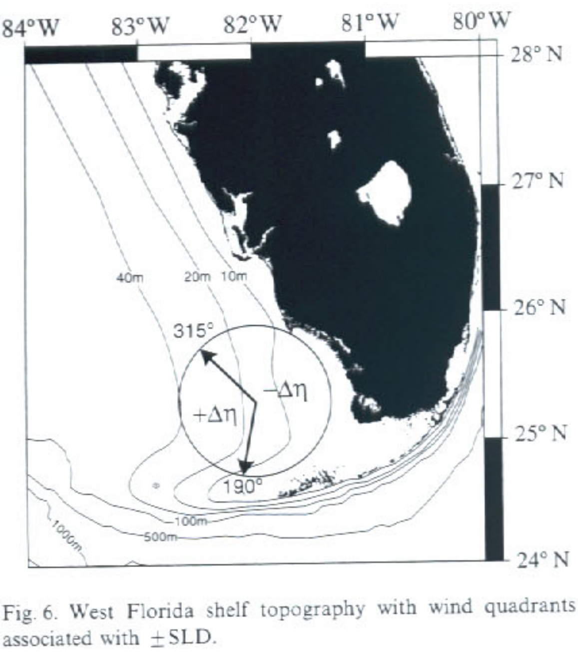

Fig. 6. West Florida shelf topography with wind quadrants associated with ±SLD.

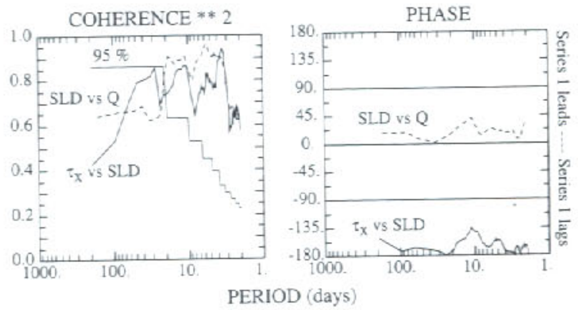

Fig. 7. Coherence and phase between the Sombrero east-west wind stress component and cross-Key SLD (solid line) and between SLD and Long Key Channel volume transport (dashed line) for October 1997–April 1998 period.

and will result in a weaker set-up along the Atlantic side of the Keys. The combined result is a negative sea level slope and accounts for the southeastward flow events through the Keys against the wind. Even stronger southeastward flows occur during the winter following cold front passages when the wind increases and shifts to eastward and southeastward (Fig. 3). Spectral analysis shows the east-west wind stress to be highly coherent and out of phase with the SLD across the Keys over the period band from 2 to 15 days (Fig. 7). A negative τ_x wind stress (westward wind) produces a positive sea level slope and a flow into Florida Bay as shown in Fig. 3. A positive τ_x wind stress (eastward wind) results in a negative SLD and outflow from Florida Bay toward the reef tract.

The dependence of cross-Key sea level slope on wind direction is clearly shown in a scatter plot of these variables (Fig. 8; see also Fig. 6 for orientation). Negative SLD occurs for winds toward 320° to about 185°, which includes summer winds from the southeast and winds from the west and northwest following cold fronts in the winter and spring. Positive SLD occurs most often for winds toward 190–315°, which are common in the fall when the winds are from the northeast and east. Negative slope values can also occur for this wind direction interval during periods of weak wind speeds or at times when sea level variations occur at periods greater than the local wind forced period band of 2 days to 2 weeks.

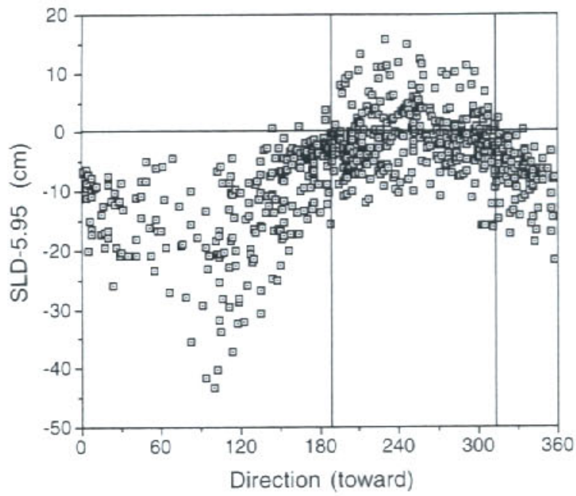

Fig. 8. Scatter plot of cross-Key SLD plus the mean SLD of −5.95 cm against Sombrero wind direction (toward). Vertical lines show the range of wind directions associated with positive SLD.

5.2. Low-frequency volume transports

Cross-Key sea level slopes appear to be the driving mechanism forcing subtidal and mean flows through the Florida Keys middle passages as shown to be their robust relationship in Figs. 3, 4 and 7. Magnitude of the transport variations through Long Key Channel ranged from −2500 to +1000 m^3/s (when multiplied by standard deviation of 487 m^3/s). Spectra analysis shows coherence levels higher than 0.9 at the 95% significance level for the energetic period band of 3–20 days, with SLD leading volume transport by 5–26 h for fluctuation periods of 4–10 days, respectively (Fig. 7). There were only two examples of the SLD and transport time series being out of phase in the entire 162 day overlapping record. At the start of the time series in October 1997 and in the middle of March 1998 there were two short events where a negative SLD occurred with positive transport against the slope, i.e. into Florida Bay. Normally, a negative SLD will cause a flow toward the reef tract. As discussed above, negative slopes arise from winds toward the northwest that occur during summer and winds toward the east and southeast that occur during winter and spring (Fig. 3). Over the entire record these southeastward transport events ranged from about −500 to −2500 m^3/s and can last from 3 to 10 days. The stronger Gulf to Atlantic flow events tend to occur in the winter and spring seasons as cold front passages cause increased winds towards the east and southeast that will set up sea level in western Florida Bay relative to the Atlantic. Southeastern flows of −1500 to −2500 m^3/s can occur in these seasons as sea level stands 20–35 cm higher in the Gulf than the Atlantic during strong eastward wind events. Positive sea level slopes force waters from Hawk Channel and the reef tract into Florida Bay (Fig. 3). Winds toward the west and southwest that occur in the fall, winter and spring are most effective in setting up the positive slopes (Figs. 3 and 7). Inflow to Florida Bay through Long Key Channel can reach magnitudes of 500–1000 m^3/s and persist for several days during these westward wind events.

5.3. Annual cycle of volume transports

Since there is considerable seasonal variation of wind forcing in the Keys one would expect a seasonal change in SLD and volume transport through the Keys passages. Fig. 9 shows that the linear relationship between SLD and transport remains strong throughout the seasons with SLD variations accounting for 86% of low-frequency transport fluctuations in the fall, 75% in winter and 72% in spring. Seasonal mean flows determined from the bias of these relationships are given in Table 3. Mean flows through Long Key Channel were toward the reef tract during all seasons. Greatest mean outflow of −338 m^3/s occurred during the winter season due to stronger wind forcing from the west following cold fronts (Fig. 3). The fall season had the weakest mean outflow of −204 m^3/s due to the more frequent winds from the east and northeast during this season that cause inflow to Florida Bay. During the summer there were no overlapping measurements of SLD and transport available for Long Key Channel. Therefore to estimate the summer mean flow we used a previous estimate of a 1 year mean flow of −262 m^3/s (Smith, 1994) together with our seasonal means to estimate the summer

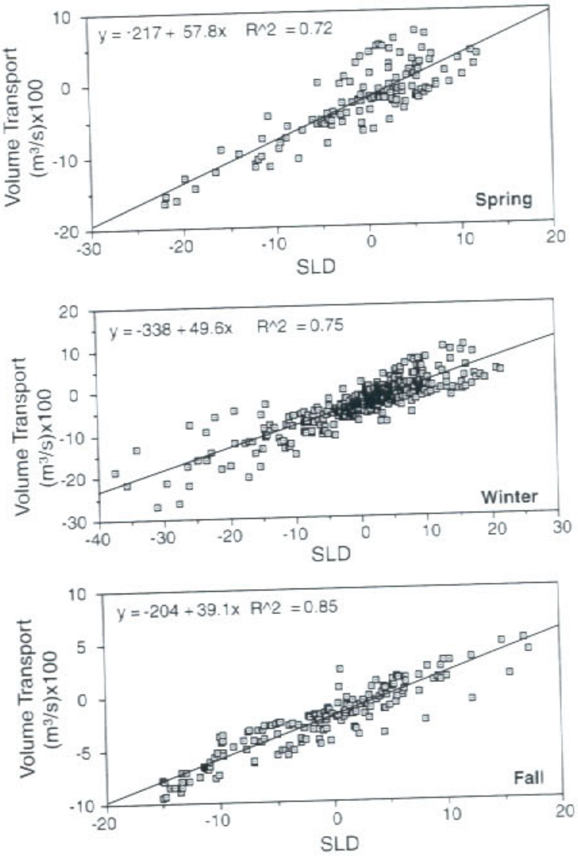

Fig. 9. Linear fit of volume transport through Long Key Channel versus SLD (Tenn.–WFB) for spring, winter, and fall seasons.

Table 3
Seasonal mean volume transports through Long Key Channel, negative is toward the reef tract

Season	Volume transport (m^3/s)
Fall	−204
Winter	−338
Spring	−217
Summer	−281
Annual average	−260

mean transport of $-281\,m^3/s$. This assumes that the 1 year estimate is representative of the long-term mean.

Lee et al. (2000) used trajectories of CODE type surface drifters deployed semi-monthly in the Shark River discharge plume to show a seasonal pattern in near surface circulation that connects the entire south Florida coastal system and appears to be dependent on the seasonal pattern of local winds. Examples are shown in Fig. 10. During the fall, drifter pathways were toward the southwest and the western Keys of the Dry Tortugas, due to influence from the fall winds toward the southwest and west. This is consistent with the weaker mean flow through Long Key Channel in the fall, as well as the frequent occurrence of positive SLD and inflows to Florida Bay. In winter and spring when the Gulf to Atlantic flow through the Keys was strongest, the drifter pathways were typically toward the southeast and through the middle Keys passages as a consequence of enhanced eastward and southeastward wind forcing following cold fronts. In summer winds are weaker and toward the northwest and the surface drifter trajectories from Shark River plume tend toward the northwest along the inner part of the west Florida shelf. The drifters that reach the west Florida shelf in the summer are then transported offshore and southwestward as wind directions shift toward the west and southwest in fall. The drifters eventually merge with the southward flowing Loop Current at the outer shelf and are carried to the Keys coastal zone.

5.4. *Mean flows*

Our vessel mounted ADCP transects show the magnitude of the combined flows through Channels 5, 2 and Long Key ranged from about $-1400\,m^3/s$ toward the southeast to $270\,m^3/s$ toward Florida Bay (Table 2). Averaging the transport over the five periods of southeastward flow gives net outflows from Florida Bay of −615, −186 and $-163\,m^3/s$ through channels Long Key, 5 and 2, respectively. The total Gulf to Atlantic flow through these channels averages near $-1000\,m^3/s$ for the southeastward flow events, which is about 100–200 times greater than peak fresh water discharges out of Shark River. Long-term measurements of volume transport through Long Key Channel show that subtidal variations range from +1000 to $-2500\,m^3/s$ (Fig. 3) and adding Channels 5 and 2 would increase this range to about +1400 to $-3500\,m^3/s$. The amplitudes of

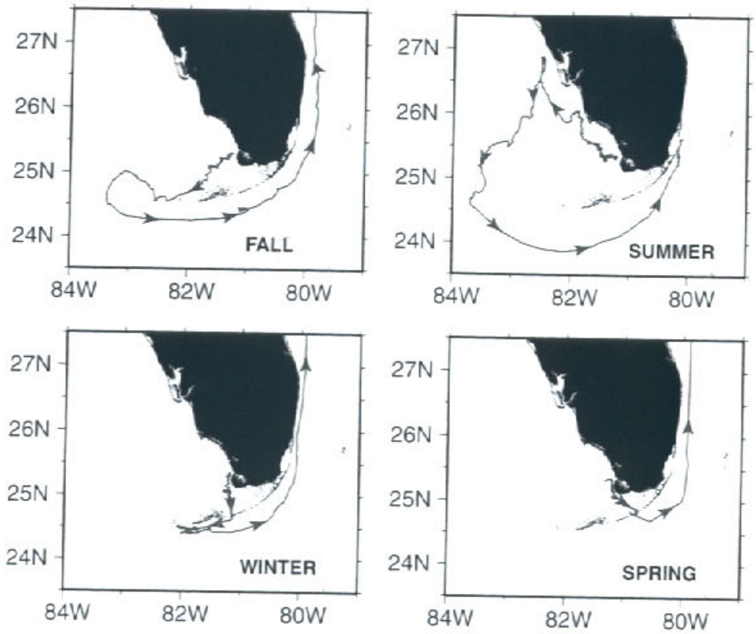

Fig. 10. Surface drifter trajectories representing seasonal circulation patterns connecting south Florida coastal waters.

these subtidal flow events are equivalent in magnitude to the mean river discharge onto the southeast US shelf by all the rivers between Florida and Cape Hatteras.

Smith (1994) estimated the annual mean outflow from Florida Bay to the reef tract through Long Key Channel of $-262\,m^3/s$ for the 1 year period from July 1992 to June 1993. This 1 year mean is remarkably close to our 162 day transport average of $-280\,m^3/s$. Importantly, the close agreement between the mean Gulf to Atlantic flows computed for different years over 6 and 12 months records indicates a relatively stable long-term mean outflow from western Florida Bay through Long Key Channel. From our vessel ADCP measurements we estimate the average flows for the six periods through Long Key, Channel 5 and 2 at −536, −111 and $-111\,m^3/s$, respectively. If we assume this ratio of flows through the channels remains relatively constant, and using the one-time flow through 7-Mile Bridge, then we can estimate the long-term mean flows through all the major passages of the middle Keys as shown in Table 4. The combined outflow through western Florida Bay by way of Long Key Channel and Channels 5 and 2 is $-370\,m^3/s$, of which Long Key Channel accounts for 70%. The flow through 7-Mile Bridge Channel is roughly estimated as $-370\,m^3/s$, which is equivalent to combined flow through the other three channels. The total net Gulf to Atlantic flow through the larger middle Keys passages is estimated at $-740\,m^3/s$.

Table 4
Long-term mean volume transports through the primary channels of the Middle Keys, negative is toward the reef tract

Channel	Volume transport (m^3/s)
Long Key	−260
Channel 5	−55
Channel 2	−55
7-Mile Bridge	−370
Total	−740

We also found that a significant number of the surface drifters deployed near Shark River were observed to move through western Florida Bay and toward the reef track through the middle Keys passages (Lee et al., 2000; Wang, 1998 and Fig. 10). Salinity patterns associated with the Shark River low-salinity plume are generally

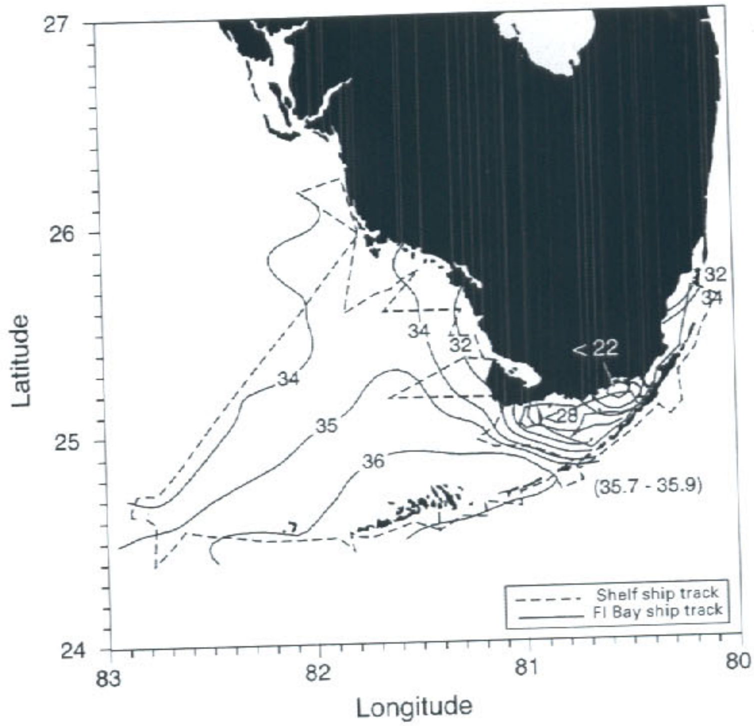

Fig. 11. Surface salinity pattern from June 8 to 16, 1998 shipboard survey showing the spatial extent of the Shark River low-salinity plume.

oriented toward the southeast with little spreading offshore of the river mouth (Fig. 11), suggesting advection by a background current, in contrast to a dynamical circulation within the plume that would cause a northwestward coastal current typical of larger northern hemisphere rivers. The low-salinity plume is observed to be vertically homogenous, except for the near-field region adjacent to the river mouth, due to the intense vertical mixing over the shallow 2–3 m depths from tidal currents that can reach 50 cm/s. Both drifter and salinity patterns indicate that the most persistent movement of the Shark River plume is toward the southeast through western Florida Bay and the middle Keys passages. This movement provides a low-salinity input to the western part of Florida Bay that helps to regulate increasing salinities in the Bay interior.

The trajectories of satellite tracked surface drifters deployed in the Shark River discharge plume clearly show strong linkages between western Florida Bay and the Florida Keys out to the Tortugas (Fig. 10). It takes 1–2 months for drifters released in the Shark River plume to reach the Florida Keys, and then <2 weeks to reach the Tortugas region due to the increased flow in the coastal countercurrent formed from alongshore easterly winds and Florida Current eddies (Lee and Williams, 1999). However if winds have a significant southerly component then drifters entering the Atlantic coastal waters in the middle Keys will turn toward the north and may become entrained in the strong northward flow of the Florida Current.

6. Conclusions

The southwest Florida shelf and Atlantic coastal zone of the Keys are connected by the passages between the islands of the middle, lower and western Keys. Movement of waters between these regions depends on a combination of local wind forced currents, and transports through the passages driven by cross-Key sea level slopes on time scales of tidal, 2 days to 2 weeks and longer-term contributions from higher sea levels in the eastern Gulf of Mexico than the Atlantic. Low-frequency variations of cross-Key sea level slopes in the middle Keys were found to be produced by sea level responding differently on the Gulf and Atlantic sides of the Keys to the same coherent wind forcing due to their different topographic and coastline configurations. Winds from the southeast, typical of the Keys region in summer, can cause a set-up of sea level in Florida Bay and weaker set-up or set-down of coastal sea level on the Atlantic side of the middle and northern Keys. This results in a Gulf to Atlantic sea level slope across the Keys and a southeast flow against the prevailing wind. Winds from the east and northeast that are frequent in the fall, winter and spring cause sea level to set-up in the Keys Atlantic coastal waters and set-down in western Florida Bay, thus forming a positive cross-Key sea level slope that drives subtidal flows toward Florida Bay through the passages. Winds from the west in the winter and spring following cold front passages will set-up sea level in western Florida Bay relative to the Keys coastal strip. This produces a Gulf to Atlantic sea level slope and outflow from western Florida Bay to the reef tract.

Our shipboard ADCP measurements show volume transports through the middle Key passages with tidal amplitudes of $\pm 6000\,m^3/s$ at Long Key Channel, $\pm 2500\,m^3/s$ at Channel 5 and $\pm 1500\,m^3/s$ at Channel 2. These amplitudes can vary by as much as $1000\,m^3/s$ and are usually unequal for the flood and ebb stages indicating significant outflow from Florida Bay. Net residual transports derived by removing the predicted tidal transports varied from about $+300\,m^3/s$ flow into Florida Bay to $-1400\,m^3/s$ outflow to the reef tract for the combined flows of the three channels. Low-frequency time series of transport through Long Key Channel was found to be highly coherent with measured sea level differences across Long Key that result from local wind forcing. Subtidal transports through Long Key Channel varied from $+1000\,m^3/s$ inflow to Florida Bay to $-2500\,m^3/s$ outflow to the reef tract.

An annual cycle of cross-Key sea level slopes and transports through the Keys passages was found with a dependence upon the seasonal cycle of local wind forcing. Maximum outflows from Florida Bay occurred in winter and spring following cold front passages when winds from the west and northwest are more common. Cold water outflows from the shallow Bay pose a potential threat to coral reefs of the middle and lower Keys during this period. Upper Keys reefs are protected from contact with these cold outbreaks due to their position northeast of the middle passages and the development of southwestward coastal currents as the wind direction veers toward the southwest following the cold front passage. Minimum outflows occurred in fall when wind directions from the northeast and east prevail causing several day periods of inflow to Florida Bay.

The long-term mean transport was found to be toward the southeast at $-260\,m^3/s$ for Long Key Channel and $-55\,m^3/s$ each for Channels 5 and 2. The flow through 7-Mile Bridge Channel is roughly estimated at $-370\,m^3/s$. The total net Gulf to Atlantic flow through the middle Keys is estimated at $-740\,m^3/s$ and appears to be supported by higher mean sea level in the eastern Gulf than on the Atlantic side of the Keys. We estimate from our sea level and transport measurements that sea level stands about 6 cm higher in western Florida Bay on the mean than in the Keys coastal zone and balances the net Gulf to Atlantic flow. Long period variations on time scales of several months or longer may occur in cross-Key sea level slopes and transports due to variations in the position of the Loop Current, but are not well understood at present.

The southeastward mean flow connecting the two shelf regions provides the source water for western Florida Bay and entrains the fresh water outflows from the Everglades through the Ten Thousand Islands. The magnitude of this mean southeast flow is about 100–200 times larger than the freshwater outflow from the Everglades, which results in a low-salinity band that is trapped along the coast of the Ten Thousand Islands and extends to the southeast into western Florida Bay.

Transport of this low-salinity water to western Florida Bay provides an additional source of fresh water that, together with discharges from Taylor Slough and Trout River in northeast Florida Bay, help to reduce hypersaline conditions in the central region of the Bay.

Trajectories of near-surface drifters deployed in the Shark River discharge plume show that there are three common pathways that connect the entire south Florida coastal system. The primary pathways are either to the southeast and through the passages of the middle Keys, which is most common during winter and spring, or southwest to the Tortugas during the fall. Advective time scales to reach the Keys Atlantic coastal zone are 1–2 months for these routes. The third pathway is to the northwest in the summer and eventual entrainment by the Loop Current, followed by transport to the Tortugas. This exchange route takes place over a 3–6 month time period. After drifters reach the Keys coastal zone they tend to either recirculate in coastal eddies and wind driven countercurrents for periods of 1–3 months, or become entrained in the Florida Current and removed from the coastal system.

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