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ON WATER RENEWAL AND SALINITY VARIABILITY IN THE NORTHEAST SUBREGION OF FLORIDA BAY

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ABSTRACT

The northeast subregion of Florida Bay receives approximately 75% of the direct freshwater runoff to the bay, most of which is retained within the subregion and has little impact on the dilution of hypersalinity development in adjacent subregions. Using direct measurements of the volume transports through connecting channels and indirectly estimating the total transport to the subregion from mean sea level variability, we show that interior basin water exchanges are weak and controlled by local wind forcing. East-west winds produced seasonally averaged throughflows of 33 and 78 $m^3 s^{-1}$ during the El Niño-influenced wet and dry seasons of 2002 and 2003, respectively, and resulted in a one year residence time for the northeast subregion. The long residence time of the interior waters is due to the confining nature of the shallow banks and mangrove borders that surround the northeast subregion, as well as the lack of significant tidal exchange. Weak interbasin exchange results in the trapping of freshwater discharge from the Everglades within the northeast subregion. Development of hypersalinity within the north-central subregion of the bay has been associated with seagrass die-off and algal blooms that can cause water quality reduction in south Florida's coastal waters, including the Florida Keys reef tract. To reduce the development of hypersalinity within this region of the bay it will be necessary to divert a portion of the Everglades flow away from the northeast basin and into Whipray Basin during the dry season. Seasonal water balance estimates made for the northeast subregion and previous estimates from the north-central region indicate that groundwater inflows to Florida Bay are negligible and probably not a factor in water quality considerations.

As part of the Comprehensive Everglades Restoration Plan (CERP; WRDA, 2000 and FFA, 2000) a major engineering effort is underway in Florida to reestablish the pre-development flow patterns of freshwater through the Everglades to Florida Bay and the Ten Thousand Islands. This effort is deemed necessary to reduce the development of hypersalinity and algal blooms within Florida Bay and adjacent regions, and improve water quality both within the bay and the downstream ecosystems of the Florida Keys National Marine Sanctuary (FKNMS). Numerical modeling experiments are underway to evaluate different freshwater flow scenarios and their influence on salinity patterns and water quality within the bay and surrounding regions (Hamrick et al., 2005). At present about 75% of direct freshwater runoff to Florida Bay occurs through a series of small creeks that discharge at the northern boundary of the northeast subregion (Fig. 1). Here we present results of recent observational studies that aim to better describe and understand the important physical processes controlling water renewal and circulation in this northeast subregion of the bay, including the fate of the freshwater discharge and its influence on salinity patterns. Comparison of these results with model experiments could benefit future water management practices.

Florida Bay is a triangular shaped patchwork of shallow (1–3 m) basins lying between the Florida mainland to the north and Florida Keys to the south (Fig. 1). Isola-

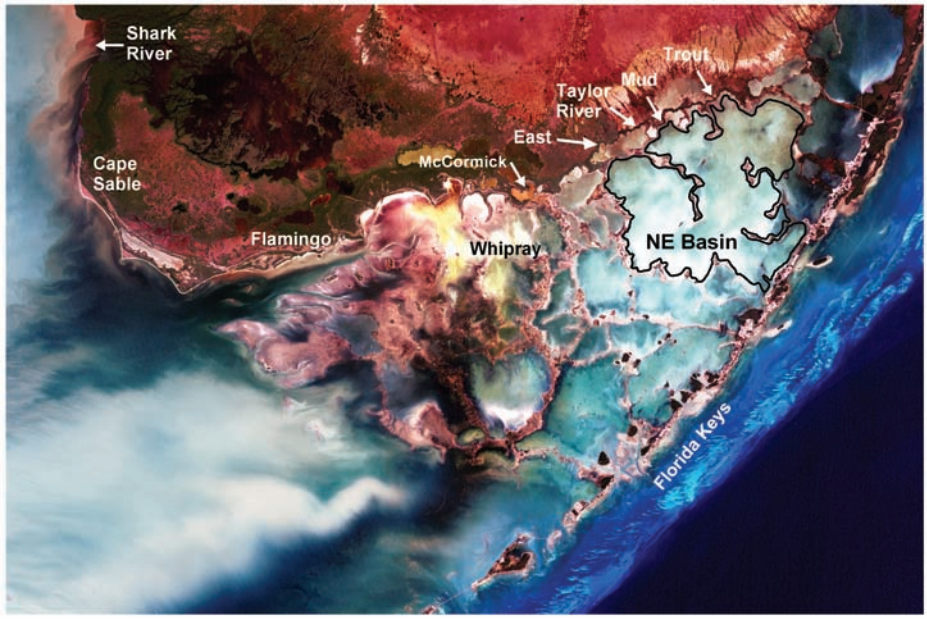

Figure 1. Aerial view of Florida Bay and southern Everglades showing the shallow banks (tan) and basins (blue and green) configuration. The northeast basin subregion and Whipray Basin in the north-central subregion are identified, as are the freshwater discharge locations (arrows).

tion of the basins occurs due to flow restriction by the broad surrounding mud banks and mangrove islands. The mud banks are largely covered by seagrass, which can be exposed at times of low water and further restrict water exchange. This lowering of sea level can occur from winds directed out of the bay toward the west or southwest (Lee et al., 2006). The mud banks are also primarily responsible for the large fall-off in tidal range, which decreases from 1.5 m at the open western connection of the bay to the southwest Florida shelf to a few cm near the northeast boundary of the bay (Wang et al., 1994). The typical climate of south Florida consists primarily of two seasons; a dry season during winter/spring and a wet season during summer/fall. The balance of freshwater flux given by $R = r + P - E$, where r is the river discharge, P is precipitation, and E is evaporation, is negative during the dry season and positive over the wet season. This leads to increasing Florida Bay salinities in the dry season and decreasing salinities in the wet season (Nuttle et al., 2000; Kelble et al., 2006; Lee et al., 2006).

The configuration of mud banks and mangrove islands within Florida Bay, as well as differences in the magnitude of volume exchange with adjacent water bodies and the isolation of river discharge in the northeast tends to separate the bay into four subregions (northeast, north-central, southeast, and western). This subdivision is clearly shown by the variation of spatial and temporal salinity patterns (Nuttle et al., 2000; Kelble et al., 2006), and those of water quality parameters (Boyer et al., 1997). Lowest salinities occur in the northeast due to the direct river discharge. Highest salinities typically occur in the north-central region due to poor water exchange, minimal freshwater discharge and shallow water depths. The largest seasonal changes in salinity take place in the northeast and north-central subregions with similar amplitudes due to their weak water exchange with surrounding regions. The southeast and west subregions have the smallest and most similar seasonal cycles due to larger

water exchange with connecting regions of the Atlantic coastal zone of the Florida Keys and southwest Florida shelf, respectively. The seasonal salinity cycles of all four regions are in phase due to the controlling nature of the south Florida net freshwater cycle (Nuttle et al., 2000; Kelble et al., 2006; Lee et al., 2006). Seasonal maximum salinities of the four subregions tend to occur following the end of the dry season in early summer (June and July) when evaporation is maximum and freshwater input is low. Minimum salinities occur one to two months following the wet season (Dec and Jan) when evaporation is minimum and river runoff, which lags precipitation by 1–2 mo, is influencing bay salinities. Hypersaline conditions (salinity > 40; all salinities reported herein measured using Practical Salinity Scale) are commonly observed during winter to early summer dry seasons in the north-central portion of the bay due to a lack of freshwater and weak water renewal rates (Nuttle et al., 2000; Kelble et al., 2006; Lee et al., 2006). We recently used direct observations of volume transports through the small channels that connect Whipray Basin in the north-central subregion to adjacent basins together with water and salt balances to estimate the magnitude of the Whipray's water renewal rate at 11 $m^3 s^{-1}$ for the 2001 dry season (Apr–Jul) and 3 $m^3 s^{-1}$ for the following wet season (Sept–Nov), which results in long residence times of 6 and 12 mo, respectively (Lee et al., 2006). In addition we found that the basin flushing was primarily driven by local wind forcing. South Florida winds are typically weak from the east and southeast during the summer, shifting to be more from the northeast during fall, with increased strength of wind events that can last 3–5 d. During winter and spring seasons, cold fronts move through the region with a period of 3–7 d, causing increased winds that rotate clockwise from southwest through northwest to northeast. The cumulative effect of the passage of these fronts drives a mean flow through the basin with inflow over the broad western banks and outflow through the eastern channels. During the fall wet season, wind events are directed toward the southwest and cause a mean flow through the basin with inflows over the eastern banks and outflows through the western and southern channels.

Methods

Field Measurements.—Our measurement strategy was the same as that developed previously for the north-central basin (Lee et al., 2006) and was aimed at determining water and salt flux between the northeast basin and adjacent subregions of Florida Bay from direct measurements of water exchange and high resolution surveying of salinity variability over dry and wet seasons. The resulting data sets were then used to estimate residence times and resolve the controlling physical processes involved. Currents, salinity, and temperature were measured in the flow channels connecting the northeast basin with the surrounding waters over 2-mo periods during the wet season of 2002 (Sept 8–Nov 18) and dry season of 2003 (Apr 2–Jun 2) (Fig. 2). Moored current meters were deployed in Boggies Creek that connects the northeast basin to Blackwater Sound near the northern boundary, and in Grouper Creek that joins the Intracoastal Waterway to Buttonwood Sound on the eastern side of the subregion. The southern boundary of the subregion is made up of Upper Cross Bank, a narrow and shallow bank that is often exposed. There are two significant openings in this bank where we deployed current meters: one in the Intra-Coastal Waterway at the east end of the bank opposite Hammer Point, and the other at the west end of the bank in Manatee Sound. Currents were measured with Sontek Argonaut SL side-looking acoustic current meters that averaged currents at mid-depth over a horizontal distance of 2–3 m from the transducers with a sample interval of 5 min and averaging time of 2 min. Each current meter was also equipped with a

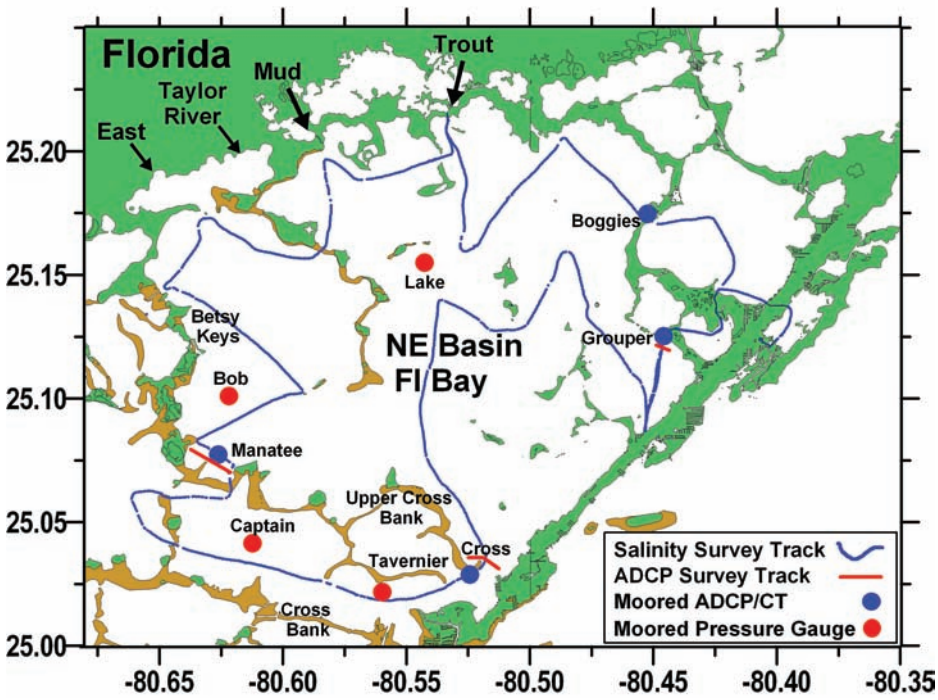

Figure 2. Location of northeast basin measurement stations for the wet season of 2002 and dry season of 2003: blue circles indicate current, temperature, and salinity stations; red circles identify bottom pressure stations; ADCP transport transects are shown with red lines and vessel salinity survey track with a blue line; estuarine creeks and small rivers discharging freshwater directly to the northeast basin are indicated by black arrows: shallow banks are light brown.

SeaBird SBE 37 MicroCat conductivity and temperature recorder set to a 30 min sampling interval. Sea level variability for the northeast subregion was determined from four Sea Bird model SBE 16 bottom pressure, conductivity and temperature recorders. Two of these instruments were deployed in the interior of the northeast subregion and two south of Upper Cross Bank (Fig. 2).

Due to mechanical problems at the Cross Bank flow site, no data were recovered during the 2002 wet season, and during the 2003 dry season, the current meter malfunctioned after May 7. All other sites had good data return. Current time series were converted to along-channel volume transport time series for the Grouper, Cross, and Manatee locations using linear correlations of currents with shipboard-measured volume transports across the channel transects. Along-channel transports were measured with an RDI 1200 kHz Acoustic Doppler Current Profiler (ADCP) mounted between the hulls of a shallow draft catamaran, the R/V Virginia K, using WinRiver software provided by the instrument manufacturer. Ensemble-averaged transports were made by averaging vessel-measured transports from consecutive pairs of ADCP transects at Cross and Manatee sections and from an ensemble of 10 consecutive transects at Grouper section. Each transect took about 4 min at Cross, 6 min at Manatee, and 1 min at Grouper, resulting in ensemble averaged transports over 8 min at Cross, 12 min at Manatee, and 10 min at Grouper. Data recovery of ADCP velocity profiles typically ranged from 80 to 100% for water depths > 1.2 m and boat speeds < 2.5 m s^{-1}. The ensemble-averaged ADCP transports were regressed against the moored measured along-channel currents averaged over the same time intervals as the vessel transects and accounted for about 97% of the measured variance of currents at Grouper, 60% at Cross, and 50% at Manatee sites. The missing transport time series at Cross after May 7 of the 2003 dry season was recreated from a regression (R^2 = 0.32) of the Cross transports with the sum of the transports through the

Boggies, Grouper, and Manatee channels. The shipboard ADCP technique could not be used at the Boggie site due to deep stands of seagrass in the shallow waters that inhibited the acoustic transmission. Therefore, transport time series were derived at this site by multiplying the cross-sectional area by the measured along-channel currents. The cross-sectional area at Boggie was 41.3 m^2, with a width and mean depth of 24.5 and 1.7 m, respectively. Sea level measurements were not available within this channel, so sea level was assumed to be constant. Sea level measurements taken by the ENP monitoring array near the Boggies, as well as our own bottom pressure measurements show a tidal range near the Boggies of only a few cm s^{-1}, which indicates that neglecting sea level variations in the transport derivations could introduce an error of approximately 3%. For the Boggies section where transports ranged from $\pm$ 20 $m^3 s^{-1}$, this error was estimated at < 1 $m^3 s^{-1}$ and was not considered significant.

Creek discharges of freshwater to the northeast basin were calculated by USGS from ADCP vertical current profiles made every 15 min and calibrated with shipboard ADCP volume transports to derive discharge time series using techniques similar to Lee and Smith (2002). The calibrated volume transports have been shown to be highly reliable due to the confined nature of the creek flows (Lee and Smith, 2002; Hittle and Zucker, 2004). The discharge at East Creek was not directly measured, but rather derived from a regression with the Mud Creek discharge (R^2 = 0.99 per Hittle and Zucker, 2004).

Synoptic spatial surveys of salinity patterns in the northeast basin and adjacent areas were made throughout the wet and dry seasons using a SeaBird 21 thermosalinograph mounted on the R/V Virginia K with a 7 s sampling interval. The vessel survey speed was kept near constant at approximately 10 m s^{-1}, which resulted in a spatial resolution of measured parameters of about 70 m. It generally took < 5 hrs to complete a detailed survey (see Fig. 2) of the entire basin and adjacent regions. Synoptic salinity surveys were also conducted monthly over the entire Florida Bay using the same vessel and instrumentation (Johns et al., 2001; Kelble et al., 2006). Each bay-wide survey was completed in 2 d, day one for the outer portion of the bay and day two for the inner area. Golden Software's Surfer program was employed to produce grid files from the underway data utilizing a Kriging procedure. These files were then used to create contoured salinity maps from the gridded fields, and also for computing the spatially-averaged salinity for the northeast basin subregion, assuming vertical well-mixed conditions, which are widely observed within these shallow basins (Kelble et al., 2006; Lee et al., 2006). Specially designed shallow water drifters were deployed several times each season in the basin interior to determine surface current trajectory patterns. These drifters consisted of small discs that floated at the surface with drogued skirts that extended 0.5 m below the discs. GPS positions were recorded internally and transmitted to ARGOS satellite. Previous testing had revealed good agreement with dye patch movement in drift direction with a small speed error caused by wind slippage (Melo et al., 2003). Local wind time series were obtained from CMAN and SeaKeys monitoring stations in the Florida Keys and northwest Florida Bay maintained as part of a cooperative agreement between Florida Institute of Oceanography (FIO) and NOAA/NDBC through the SEAKEYS Program. Previous investigations have found that synoptic winds are highly coherent over the study area (Lee and Williams, 1999). Measurement of freshwater discharge into Florida Bay was made by USGS for all significant river input locations (USGS, 2005; Fig. 1), and daily average discharges for 2002 and 2003 were provided by C. Hittle, USGS. All time series data were first smoothed slightly with a 3 Hour Low-Pass (3HLP) filter and subsampled at hourly intervals, then filtered with a 40 Hour Low-Pass (40HLP) Lanczos filter and subsampled every 6 hrs. The 40 HLP removes tidal and sea breeze influences to reveal low-frequency (subtidal) variations.

Water Balance.—Because direct measurement of the total water exchange between interior basins of Florida Bay is not possible with current meter instrumentation, we used the method of Lee et al. (2006) to determine the total change in water volume over time, Q_T, from sea level variations for the northeast basin. The total flow, Q_T, into or out of the northeast basin must balance the sum of the flows through the four measured channels, Q_c, plus the

flows over the surrounding shallow banks and any small channels that were not measured, Q_b, written as:

$$Q_T = Q_c + Q_b \quad (1)$$

Changes in sea level were measured with an array of four bottom pressure stations (Fig. 2). Two of the gauges were located in the interior of the northeast basin and two in the connecting basin to the south between Upper Cross Bank and Cross Bank. The two gauges within the interior of northeast basin were used to estimate time series of mean sea level changes for the basin, which when multiplied by the basin surface area and demeaned provides time series of basin total volume anomaly, $\partial V_{NE}/\partial t$, which must balance the total flow, Q_T, in or out of the basin. Mean volume was computed as the product of the basin surface area and mean water depth. The surface area was calculated with ArcView software as the area within the outer perimeter of the basin. The outer perimeter follows a line that traces the inside edges of the banks and mangrove borders, so that the basin area does not include the surrounding banks. Mean depths were also computed from ArcView software by averaging the basin mean sea level bathymetric data. Using equation (1) above, where the total flow (Q_T) is estimated from sea level variability and knowing the combined channel flow (Q_c), we computed the combined flow over the banks plus small ungauged channels (Q_b).

Results

Freshwater Discharge.—Discharge of freshwater to Florida Bay occurs through a series of small estuarine creeks along the northern mangrove border (Figs. 1, 2). First order statistics of the discharge from the four more significant creeks that discharge to the northeast basin (Mud, Trout and East Creeks, plus Taylor River) sum to 12.1 $m^3 s^{-1}$ over the wet season and 4.2 $m^3 s^{-1}$ for the dry season with about half of the freshwater inflow occurring through Trout Creek alone (Table 1). Mean flows from the other three creeks were approximately equal at about 1.5 $m^3 s^{-1}$ for the wet season and 0.6 $m^3 s^{-1}$ for the dry season. Low-frequency variations of freshwater input were also much greater at Trout Creek than at the other locations with standard deviations of 16.2 and 9.3 for the wet and dry seasons, respectively, which were nearly an order of magnitude greater than the other creeks. Maximum and minimum flows were also much greater for Trout Creek, reaching inflow rates of 35 $m^3 s^{-1}$ during the wet season and 22 $m^3 s^{-1}$ during the dry season compared to extreme values of only 2–7 $m^3 s^{-1}$ for each of the other creeks. Negative flows represent outflows from the basin to the bordering mangrove regions, coastal lagoons and upland areas and have strong correlation with winds toward the northeast (plot not shown).

Salinity.—A time sequence of surface salinity patterns in the northeast basin and adjoining regions during the wet season of 2002 and dry season of 2003 was created from selected synoptic surveys of the entire Florida Bay (Fig. 3A,E,I) and detailed surveys of the northeast basin (Fig. 3B–D, F–H). The dominant pattern of salinity in the northeast basin consists of a band of lower salinities emanating from the two largest freshwater discharge sources, Trout Creek and Taylor River on the northern boundary, juxtaposed with an area of maximum salinity in the southeastern part of the basin near Tavernier Creek. This pattern was maintained over both seasons with salinity gradients between the two extremes tending to align along the major axis of Florida Bay in a northeast to southwest direction. During the wet season minimum salinities near Trout Creek were near zero and maximum salinities near Tavernier

Table 1. First order statistics of 40 HLP freshwater discharge (m^3 s^{-1}) from estuarine creeks connecting to the northeast basin for (A) wet season (Sept 8–Nov 19, 2002) and (B) dry season (Apr 2–Jun 2, 2003) observation periods. Positive values represent inflows to the basin.

A. Wet Season	Mean	± SD	Max	Min	Range	Variance
Trout	7.4	16.2	35.2	–52.8	87.9	261.5
Taylor	1.5	1.7	4.0	–5.1	9.1	2.9
Mud	1.6	2.2	4.6	–7.0	11.6	4.9
East	1.6	1.8	4.1	–5.5	9.6	3.4
Net	12.1					
B. Dry Season						
Trout	2.3	9.3	22.1	–19.8	42.0	85.8
Taylor	0.7	1.5	3.8	–2.7	6.5	2.2
Mud	0.5	1.7	4.0	–3.5	7.5	3.0
East	0.7	1.4	3.6	–2.6	6.2	2.0
Net	4.2					

Creek were 32–34 (Fig. 3B,C,D). Over the dry season, the minimum salinities off Trout Creek increased to near 20, whereas the maximum salinities near Tavernier Creek continued to be about 34 (Fig. 3F–H), showing that the maximum seasonal change in salinity occurred near the mouth of the freshwater sources due to weak river discharge in the dry season (Fig. 4). The smallest seasonal change occurred near Tavernier Creek, which exchanges water with the Atlantic coastal waters of the Keys and tends to buffer the magnitude of the seasonal salinity cycle in this region. Also it appears that the shallow and often exposed Upper Cross Bank lying north of Tavernier Creek tends to inhibit the southward spread of riverine waters across this bank, causing large north-south salinity gradients over the bank. The low-salinity plumes from Trout Creek and Taylor River merge toward the southwest resulting in a low-salinity band that is trapped along the northern boundary and spreads southwest and south along the eastern side of Black Betsy Keys (Fig. 3) following the general wind direction toward the west. The presence of the low-salinity band along the northwestern boundary of the basin and elevated salinities or even hypersalinity conditions in Whipray Basin to the west results in very large salinity gradients across the wide and shallow bank of Crocodile Dragover that separates the north-central and northeast basins (Fig. 3; Kelble et al., 2006; Lee et al., 2006).

The seasonal cycle of basin-averaged salinity together with a 5-d running average of the total creek discharge to the northeast basin indicate that the minimum mean basin salinity of 20.7 occurred on Sept 7 and then increased at a mean rate of approximately 1.5 mo^{-1} to a maximum value of 31.8 on Apr 22 (Fig. 4). As expected, the seasonal change of mean basin salinity is inversely coupled to the total creek freshwater discharge to the basin with very little phase lag. In addition, it also appears that changes to basin-averaged salinity of 2–3 salinity units on several-day time scales are also significantly influenced by several-day variations of creek discharge.

Transports.—Time series of volume transports for both high-frequency (3HLP filter) and low-frequency (40HLP filter) channel flows connecting the northeast basin for both seasons show that the derived volume transport time series are in close agreement with shipboard ADCP measured transports for the narrow confined channel of Grouper, and also in reasonable agreement in the wider channels of Cross and Manatee, although with greater scatter (Figs. 5, 6; Table 2). Also, tidal forcing

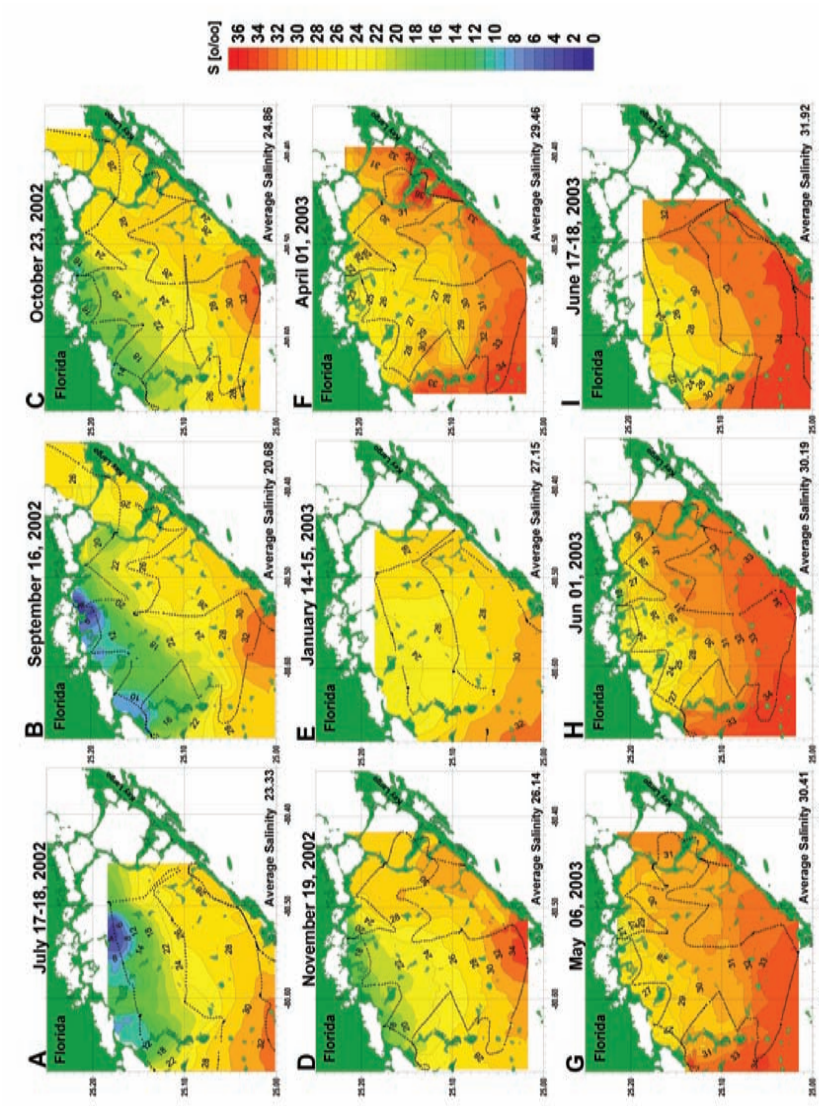

Figure 3. Northeast basin surface salinity from surveys of the R/V Virginia K using continuous underway measurement for (A) Jul 17–18, (B) Sept 16, (C) Oct 23, and (D) Nov 19 of the 2002 wet season; and (E) Jan 14–15, (F) Apr 1, (G) May 6, (H) Jun 1, and (I) Jun 17–18 of the 2003 dry season. Vessel track is shown with a dotted line. The basin spatially-averaged salinity is given at the lower right of each panel.

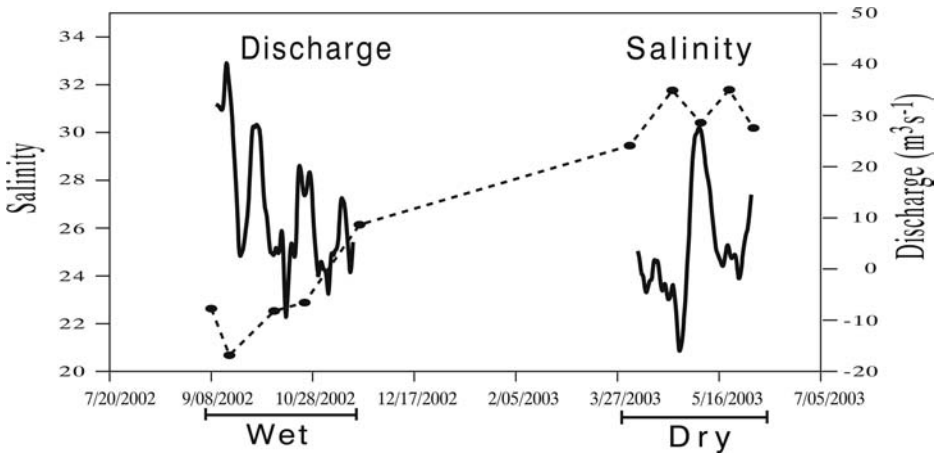

Figure 4. Northeast basin average salinity and 5 d average net creek discharge for dry and wet seasons of 2002–2003.

is stronger at the southern channels through Upper Cross Bank, which are closer to Tavernier Creek that opens to the Keys Atlantic coastal zone. The more northern flow channels have weaker tidal flows since they connect to Buttonwood Sound and Black Water Sound that are further displaced from the Atlantic Ocean and Gulf tides. The strongest tidal flow was observed at Cross where semi-diurnal tidal transports varied from ±100–150 $m^3 s^{-1}$ and accounted for about 70% of the total flow variability. Tidal flows were weaker at Manatee with variations of ±25–50 $m^3 s^{-1}$, but still accounted for about 80% of the total flow variability. At Grouper tidal flows ranged from ±5–10 $m^3 s^{-1}$ and represented only about 10%–12% of the total flow variance. Smallest tidal flows were at the Boggies, typically 2–5 $m^3 s^{-1}$ and only accounted for about 8% of the total variability. Consequently, low-frequency transport variability, which has a strong local wind influence, had the largest effect on total flow variations at the Boggies and Grouper channels and the smallest influence at Cross and Manatee. However, due to their larger cross-sectional areas Cross and Manatee had the largest subtidal transport variations from ±40–60 $m^3 s^{-1}$, where Grouper and Boggies were ±10–20 $m^3 s^{-1}$.

Station to station relationships of subtidal transport variations and responses to local wind forcing are more clearly viewed by plotting all low-frequency transport time series together with the U and V wind components for each season (Figs. 7, 8). Subtidal changes in flow through the Boggies and Grouper channels were highly coherent ($R^2 > 0.96$) and in phase during both seasons. Therefore, for clarity only the flow at Grouper is not shown on Figures 7 and 8. Flows through these channels are also highly correlated ($R^2 > 0.70$) and out of phase with the east-west wind component. Winds toward the west occurred with inflows and winds toward the east were associated with outflows through these channels. The relationships between flows through the wider southern openings of the northeast basin were not as consistent or clearly defined as the northern pair of openings (Fig. 8). The dry season was used in this consideration because the Cross current meter did not function properly during the wet season. During the dry season, Cross channel flows were significantly positively correlated with flows through Grouper and Boggies, and negatively correlated with Manatee and east-west winds (Fig. 8), whereas Manatee was positively correlated with the east-west winds. This suggests that westward winds cause inflows

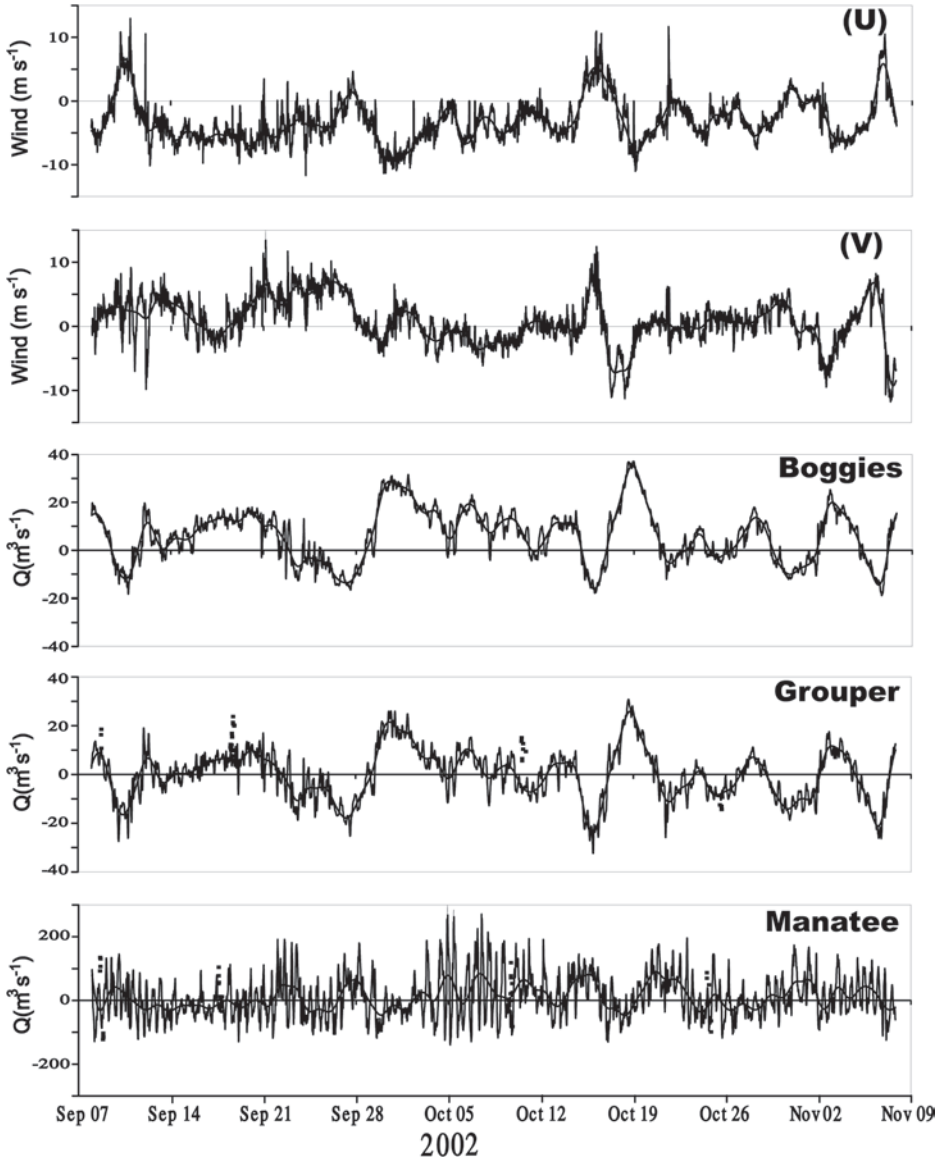

Figure 5. 3 and 40 HLP volume transports derived for the major flow channels to northeast basin for the wet season 2002. Positive values are inflows and negative are outflows. Also shown are the shipboard derived ADCP transports superimposed on the time series as solid dots, and east-west (U) and north-south (V) wind components from Molasses Reef.

to the northeast basin through channels on its eastern side and outflows through its western channels. The opposite occurs for eastward winds, with outflows in the east and inflows on the western side of the basin. North-south winds were not significantly correlated to flows at any of the channels. At times when the wind is blowing toward the northeast or southwest (U and V components have the same sign) channels flows tend to be significant. Winds toward the northeast produce negative flow in the eastern channels and positive flow in the western channel, and the reverse for winds toward the southwest. Thus for a wind toward the southwest, an

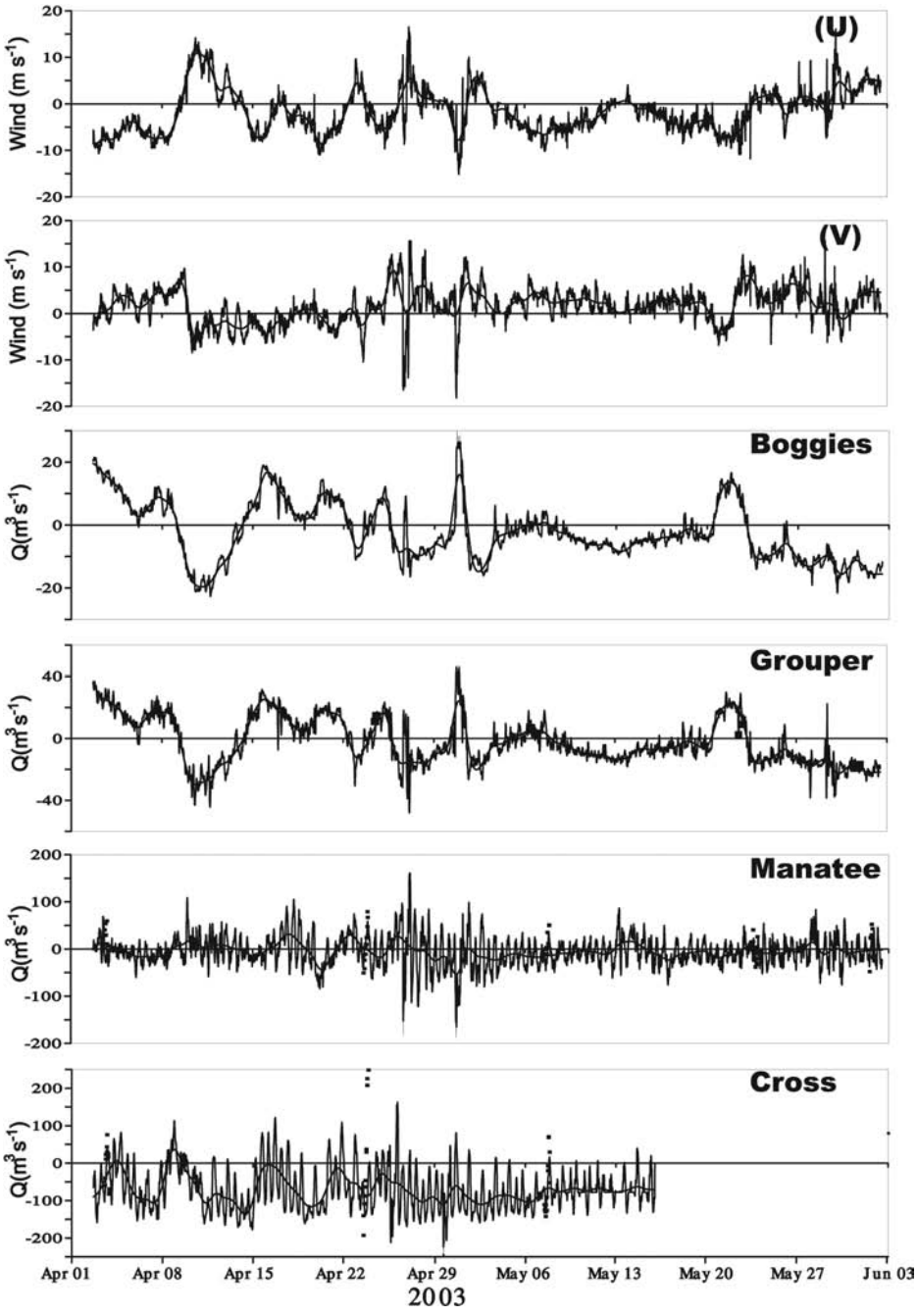

Figure 6. 3 and 40 HLP volume transports derived for the major flow channels to northeast basin for the dry season 2003. Positive values are inflows and negative are outflows. Also shown are the shipboard derived ADCP transports superimposed on the time series as solid dots, and east-west (U) and north-south (V) wind components from Molasses Reef.

Table 2. First order statistics of (A) 3 HLP along-channel transports ($m^3 s^{-1}$), and (B) 40 HLP along-channel transports ($m^3 s^{-1}$) from channels to the northeast basin and Molasses Reef wind components ($m s^{-1}$) over record lengths during 2002 dry season and 2003 wet season. For (B), percent of total variance due to subtidal variations is also provided.

	Start m/d/h	End m/d/h	Data Pts	Mean	SD ±	Max	Min	Range	Var	% Var low-freq
(A) Wet Season 2002										
Wind U	9/8/0030	11/19/1130	1,740	–3.0	3.6	13.5	–10.6	24.1	13.1	
Wind V	9/8/0030	11/19/1130	1,740	0.5	4.0	11.1	–15.1	26.1	16.1	
Boggies	9/8/0030	11/19/1130	1,740	5.7	11.4	37.5	–21.4	58.9	131.1	
Grouper	9/8/0030	11/19/1130	1,740	–0.4	10.8	30.6	–39.2	69.8	117.4	
Cross	no data									
Manatee	9/8/0030	11/19/1130	1,740	10.1	62.4	277.8	–136.0	413.8	3,905.4	
(A) Dry Season 2003										
Wind U	4/2/1630	6/2/1130	1,460	–1.6	4.6	14.4	–13.0	27.4	21.1	
Wind V	4/2/1630	6/2/1130	1,460	1.6	3.8	13.2	–16.0	29.3	14.2	
Boggies	4/2/1630	6/2/1130	1,460	–2.2	9.3	28.5	–22.5	51.0	86.6	
Grouper	4/2/1630	6/2/1130	1,460	–2.1	15.1	44.8	–46.1	90.9	227.9	
Cross	4/2/1630	5/15/2330	1,040	–70.3	58.2	166.8	–191.8	358.6	3,384.1	
Manatee	4/2/1630	6/2/1130	1,460	–5.0	30.7	161.2	–176.6	337.9	944.3	
(B) Wet Season 2002										
Wind U	9/7/0030	11/18/0630	290	–3.0	3.3	9.2	–9.3	18.6	11.0	84.0
Wind V	9/7/0030	11/18/0630	290	0.5	3.7	9.1	–10.3	19.4	13.5	83.8
Boggies	9/7/0030	11/18/0630	290	5.7	11.0	35.1	–18.9	54.0	120.1	91.6
Grouper	9/7/0030	11/18/0630	290	–0.4	10.1	25.8	–29.2	55.0	101.6	86.5
Cross	no data									
Manatee	9/7/0030	11/18/0630	290	10.5	33.6	90.1	–54.6	144.6	1,132.0	29.0
(B) Dry Season 2003										
Wind U	4/2/1630	6/2/1030	244	–1.6	4.3	10.9	–8.6	19.4	18.1	85.8
Wind V	4/2/1630	6/2/1030	244	1.6	2.9	9.2	–5.7	14.9	8.3	58.4
Boggies	4/2/1630	6/2/1030	244	–2.2	9.0	19.6	–19.6	39.3	80.2	92.6
Grouper	4/2/1630	6/2/1030	244	–2.0	14.3	35.4	–29.7	65.2	205.0	90.0
Cross	4/2/1630	5/15/2230	174	–70.3	32.9	35.9	–135.3	171.2	1,081.0	31.9
Manatee	4/2/1630	6/2/1030	244	–5.0	13.6	31.4	–53.5	84.9	186.0	19.7

inflow occurs through the eastern channels and outflow at Manatee, and for a northeastward wind, an inflow occurs at Manatee and outflow at the eastern channels. A similar pattern of channel flows occurred during the wet season with strong positive correlation between flows at Boggies and Grouper, both of which were negatively correlated with transports at Manatee (Fig. 7). The responses to local winds were similar to the dry season, with zonal winds negatively correlated with flows through Boggies and Grouper and positively correlated with Manatee transports. The flow response to meridional winds showed more significant responses when winds were aligned with the major axis of Florida Bay. Winds toward the northeast produced inflows through Manatee and outflows through Boggies and Grouper, whereas wind toward the southwest resulted in the opposite condition of inflows through Boggies and Grouper creeks and outflows through Manatee. The typical magnitude of subtidal flow variations was about ± 20 $m^3 s^{-1}$ at Boggies and Grouper channels with little seasonal difference, whereas at Manatee, transport magnitudes were ± 30 m^3

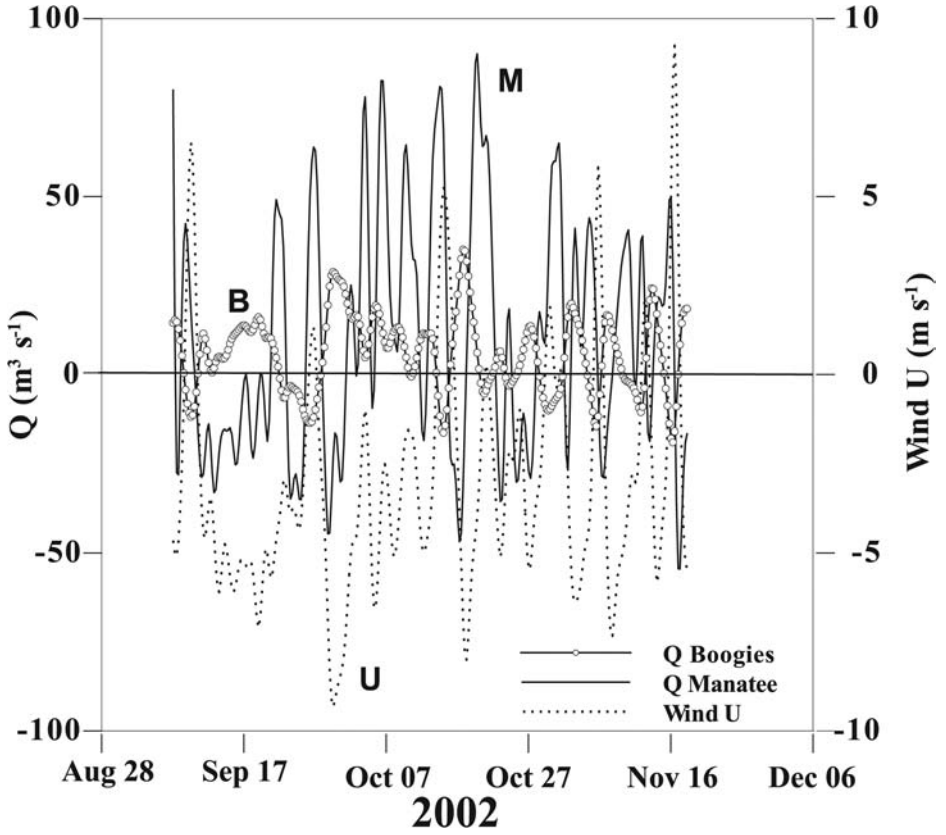

Figure 7. Subtidal volume transports (Q) from Boggies (B) and Manatee (M) channels and east-west winds (U) for wet season 2002.

s^{-1} during the dry season and about a factor of two larger during the wet season at ± 40–60 $m^3 s^{-1}$.

Seasonal Mean Flows and Subtidal Salt Flux.—The 40 HLP times series of volume transport (Q) and salinity (S) were used to compute the seasonal averaged salt flux (Q´S´) from low-frequency wind events for each of the channel measurement sites. Seasonal mean flows and salinities are generally well-resolved over the wet and dry seasons with mean quantities larger or equivalent to their standard errors (Table 3). However, longer data records are indicated to fully resolve robust estimates of seasonal average salt flux produced by subtidal processes. During the wet season there was a mean inflow at Boggies (+5.6) and Manatee (+10.4) channels at the northeast and southwest openings to the basin, respectively. The mean flow through Grouper was near zero. Mean salinities in the channels reflect the general salinity patterns of the region with higher salinities found in the east and south portions of the basin. The average salt flux for the wet season was negative for each channel although not significantly different from zero net flux. During the dry season mean outflow at Cross (–70 $m^3 s^{-1}$) was about an order of magnitude larger than at the other channels and comprised about 90% of the net outflow of –79.5 $m^3 s^{-1}$. Mean salinities in the channels paralleled basin average salinities (Fig. 4) and were 4–7 salinity units greater than the wet season, with the largest changes occurring at the northeast and southwest channels. Very little seasonal change occurred at Cross in the southeast

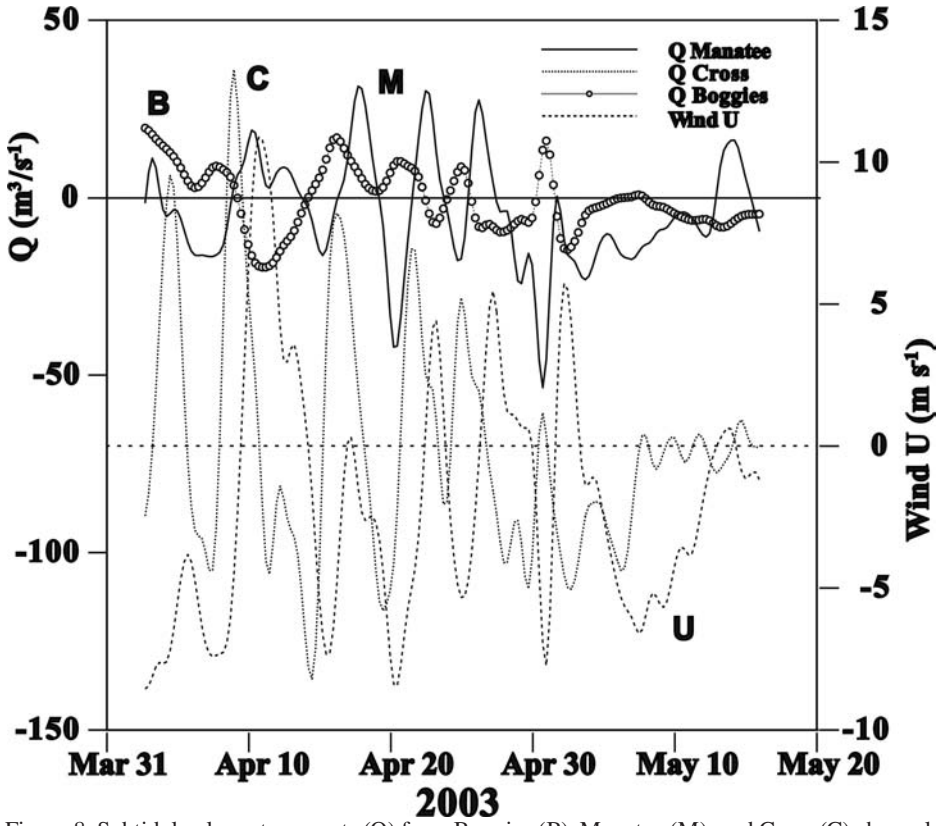

Figure 8. Subtidal volume transports (Q) from Boggies (B), Manatee (M), and Cross (C) channels and east-west winds (U) for dry season 2003.

part of the basin as was shown previously by the salinity survey data (Fig. 3). Channel salt flux estimates for the dry season and the net salt flux were not significantly different from zero (Table 3).

Residence Times.—Subtidal time series of the flow balance for the northeast basin as given by Egn. 1 indicate that during the wet season total flow, Q_T, into and out of the northeast basin typically reached magnitudes of ± 100 $m^3 s^{-1}$, whereas during the dry season total flow events ranged over ± 50 $m^3 s^{-1}$ (Fig. 9; Table 4). The total channel and bank flows tended to be out of phase during both seasons and with equal magnitudes during the dry season of about ± 50 $m^3 s^{-1}$, whereas during the wet season bank flow events where much stronger at ± 120 $m^3 s^{-1}$ and the channel flows were ± 40 $m^3 s^{-1}$.

On seasonal time scales, the average total flow for northeast basin was small and there was a near balance between mean bank flow and channel flow as would be expected from Eqn. 1 when Q_T is small (Table 4). During the wet season there was a mean inflow over the banks of about 38 $m^3 s^{-1}$ that was nearly balanced by mean outflow through the channels of –33 $m^3 s^{-1}$, resulting in a mean basin throughflow of about 35 $m^3 s^{-1}$. The mean volume of northeast basin was estimated at 4.41×10^8 m^3 and assuming this is constant, a mean throughflow of 35 $m^3 s^{-1}$ would take approximately 5 mo to exchange an equivalent water volume. For the dry season there was also a mean inflow over the banks that was more than twice the magnitude of

Table 3. Seasonal average volume transport (Q), salinity (S), and subtidal salt flux (Q′S′) from 40 HLP moored time series for wet season of 2002 and dry season of 2003. Also shown are the standard errors of mean (SE) computed as the ratio of the standard deviation to the square root of the degrees of freedom, where the degrees of freedom are determined from the ratio of the record length in days to the decorrelation time scale, as per Press et al. (1992). Positive values represent inflows to the basin.

Wet Season 2002						
Station	Q ($m^3 s^{-1}$)	± SE ($m^3 s^{-1}$)	S	± SE	Q′S′ ($m^3 s^{-1}$)	± SE ($m^3 s^{-1}$)
Boggies	5.6	2.6	24.40	0.7	–5.4	7.7
Grouper	–0.46	2.4	27.95	0.3	–1.6	2.8
Cross	no data		33.16	0.3	no data	
Manatee	10.4	7.9	24.90	0.6	–5.7	17.2
Dry Season 2003						
Station						
Boggies	–2.2	2.6	31.32	0.25	–2.47	4.6
Grouper	–2.0	4.1	32.01	0.21	–2.39	4.8
Cross	–70.3	11.2	34.48	0.34	8.97	63.9
Manatee	–5.0	3.9	32.60	0.34	–3.99	11.0
Net	–79.5				0.12	

the wet season at about 80 $m^3 s^{-1}$ and was nearly balanced by a mean outflow through the channels of –78 $m^3 s^{-1}$. A mean throughflow of this magnitude would require approximately 2 mo to exchange an equivalent water volume. On annual time scales the annual mean throughflow is estimated at 57 $m^3 s^{-1}$, indicating that the volume of northeast basin could potentially be replaced in 3 mo.

The source of the seasonally-averaged basin throughflows can be understood by comparing the total bank and channel flows to local winds (Fig. 10A,B). During both seasons the east-west component of the wind was significantly correlated with both the bank flows and channel flows, although the relationship with channel flows was not as strong. In addition, the east-west wind events tended to be in-phase with bank flows and out of phase with the channel flows, indicating that eastward winds caused net inflows over the banks and net outflows through the measured channels. The opposite was true of westward winds, which caused net inflows through the channels and net basin outflows over the banks. By comparing individual channel flows to winds (Figs. 7,8) it is clear that eastward winds, common in winter and spring during cold front passages, caused outflows through the channels on the eastern side of the basin (Boggies, Grouper, and Cross) and therefore the net bank inflows must be occurring over the western and southwestern banks. The opposite occurs for westward winds with inflows through the eastern channels and basin outflows over the western and southwestern banks. By rotating the wind coordinates we found that the basin throughflow was most responsive to winds rotated by about 40° so that +U winds were toward 130°T (true). Winds toward this direction are common during the winter/spring period during cold front passages and tend to be stronger than other seasons, which may explain the larger mean throughflow for the dry season.

Total flow for the northeast basin can also be expressed in terms of the sum of the contributions from important known physical processes using a seasonal water balance approach as in Lee et al. (2006):

$$Q_T = Q_w + Q_g + r + P + E \tag{2}$$

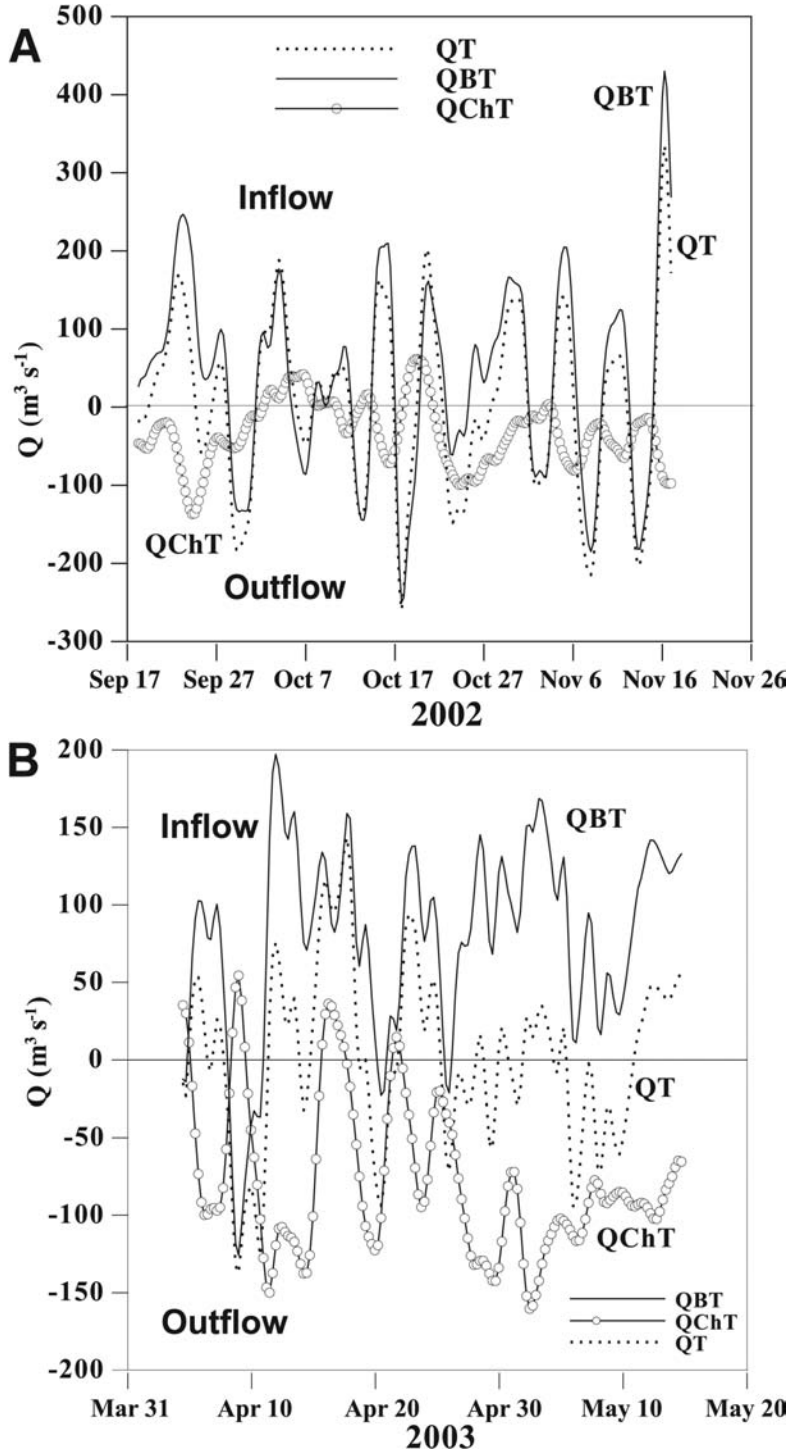

Figure 9 (A) Flows to northeast basin during wet season of 2002: total flow (QT), total bank flow (QBT) and total channel flow (QChT). (B) Flows to northeast basin during dry season of 2003: total flow (QT), total bank flow (QBT), and total channel flow (QChT).

Table 4. Seasonal and annual means of total transport (Q_T) from northeast basin volume anomalies, total measured channel transport (Q_c) and residual bank transport (Q_b) from $Q_b = Q_T - Q_c$ in $m^3\ s^{-1}$ for 2002 wet season and 2003 dry season. Standard deviations are shown with ±. The exchange time is the time required to transport an equivalent mean basin volume by the net inflow over the banks and outflow through the channels. Physical dimensions of the northeast basin are: mean depth, h = 1.5 m, surface area, $A = 2.94 \times 10^8 = 294\ km^2$, mean volume, $V_{NE} = 4.41 \times 10^8\ m^3$.

Transport	Wet season ± SD	Dry season ± SD	Annual mean
Q_T	5.3 ± 113.2	1.8 ± 56.8	3.6
Q_c	–32.7 ± 41.9	–77.8 ± 50.1	–55.2 ± 46.0
Q_b	38.0 ± 121.4	79.6 ± 62.5	58.8 ± 92.0
Exchange time (mo)	4.8	2.2	3.0

where Q_w is the total seasonal average transport due to local wind forcing and is assumed to be negligible since wind-driven throughflows should balance over a seasonal time scale, Q_g is an unknown groundwater inflow to the basin, and r is direct river discharge to the basin (Table 1). Q_T was determined above (Eqn. 1 and Table 4). Monthly values of precipitation, *P*, and evaporation, *E*, were obtained from Kelble et al. (2006). Their precipitation values were originally from NOAA's National Climate Data Center for Division 7 consisting of Florida Bay and the Florida Keys, and they used a bulk aerodynamic flux equation derived by Pond et al. (1974) to estimate E from atmospheric observations taken at the Long Key National Data Buoy Center CMAN station located in Florida Bay, close to the northeast basin.

During the wet season there was a net freshwater flux to the basin of 7.1 $m^3\ s^{-1}$ ($r + P + E$) that resulted in a small negative groundwater outflow or downwelling of –1.8 $m^3\ s^{-1}$ to balance the seasonal mean total flow (Table 5). Mean river discharge decreased over the dry season and precipitation increased, causing a net freshwater flux to the basin of 2.2 $m^3\ s^{-1}$ that required a weak groundwater outflow of –0.4 $m^3\ s^{-1}$ to compensate for the mean total flow.

Discussion

Salinity.—Observational and modeling studies of the spatial and temporal variability of salinity patterns within Florida Bay have shown the northeast subregion to consistently have the lowest salinity and one of the largest seasonal changes in mean basin salinity (Boyer et al., 1997; Nuttle et al., 2000; Kelble et al., 2006). The minimum salinity designation comes about due to direct discharge of freshwater through a series of estuarine creeks along the northern boundary of the northeast basin. Approximately 75% of the total runoff to Florida Bay occurs in the northeast basin, with another 20% to nearby Long Sound at the northeastern border and 5% to the north-central region. Interestingly, the highest salinities are found in the north-central subregion, which is adjacent to the northeast basin, although separated by a broad, shallow bank and a north-south extension of mangrove islands, the Betsy Keys. The presence of this bank inhibits water exchange between the two subregions and adds to the development of hypersalinity conditions in the north-central subregion while continuing lower salinities in the northeast and causing large negative salinity gradients across the bank (Lee et al., 2006). The low salinity characteristic of the northeast basin is further maintained by the lack of any direct connections to the Atlantic coastal waters of the Florida Keys, as occurs in the southeast subregion through Snake Creek, Tavernier Creek, and Lignumvitae Channel, providing tidal

Table 5. Values for annual water balance model for the northeast basin during wet and dry seasons of 2002 and 2003, respectively (in $m^3 s^{-1}$). Positive values represent inflows to the basin and negative values are for basin outflows.

	$+ Q_g$	$+ r$	$+ P$	$+ E$	$=$	Q_T
Wet	–1.8	12.1	8.7	–13.7		5.3
Dry	–0.4	4.2	12.0	–14.0		1.8
Annual average	–1.1	8.2	10.4	–13.9		3.6

exchange that aids in buffering large changes in salinity in that region. In addition, the shallow depth of Upper Cross Bank provides separation of the northeast and southeast subregions, and further isolates the low-salinity northeast region. Detailed salinity surveys during wet and dry seasons show the creek runoff to blend into a low-salinity band along the northern boundary and elongate toward the west and southwest in the direction of the prevailing winds. Changes to mean basin salinity have an immediate response to creek runoff on time scales as short as a few days (see Fig. 4). Kelble et al. (2006) previously reported a 2 mo lag between runoff and mean salinity of the northeast subregion based on statistical analysis of a 7 yr data set of monthly surveys for the entire bay. With the greater temporal and spatial resolution of our northeast basin surveys we are able to reduce this lag time to just a few days and show that changes in mean basin salinity are highly dependent on freshwater runoff. This difference in time lags is due to three factors: (1) sampling intervals—this study had daily surveys for three consecutive days approximately every 2 wks, whereas Kelble et al. (2006) had single monthly surveys; (2) subregion-delineation—Kelble et al. (2006) included the basin between Upper Cross and Cross bank which is further removed from creek discharge and thus a longer lag than the subregion defined here; and (3) sampling locations—our surveys were conducted closer to the creek mouths (Fig. 3B) than were the Kelble et al. (2006) surveys (Fig. 3A).

Comparing changes in monthly mean basin salinities in the north-central subregion to that of the northeast, Kelble et al. (2006) found that the salinity in the north-central region responded faster to changes in precipitation, evaporation, or runoff than in the northeast. For precipitation, the lag in basin salinity was 2-mo in the north-central subregion and 4-mo in the northeast, and for runoff, the lag was 1-mo in the north-central and 2-mo in the northeast. The faster response in the north-central subregion was in large part due to the shallow bathymetry (mean depth of 0.65 m compared to 1.5 m for the northeast region) and an order of magnitude smaller mean volume in the north-central subregion, which allows salts to concentrate or dilute more rapidly. However, by far the greatest amount of runoff to Florida Bay is concentrated in the northeast (94% when including Long Bay, a coastal lagoon located on the northeast boundary of the subregion), and this results in large differences in net freshwater supply between the northeast and north-central sub-regions. The annual rate of freshwater input via runoff is 84.6 cm yr^{-1} in the northeast subregion and only 5.9 cm yr^{-1} in the north-central subregion. Assuming precipitation and evaporation are uniform over Florida Bay at rates of 111 cm yr^{-1} and 136 cm yr^{-1}, respectively (Kelble et al., 2006), then the annual net freshwater supply to the northeast subregion becomes 59.6 cm yr^{-1}, whereas for the north-central subregion there is a negative or loss of water at a rate of –19.1 cm yr^{-1}. These differences in net freshwater supply, and lags between salinity and freshwater input, result in the shallow north-central subregion responding more rapidly to freshwater inputs, whereas the northeast region

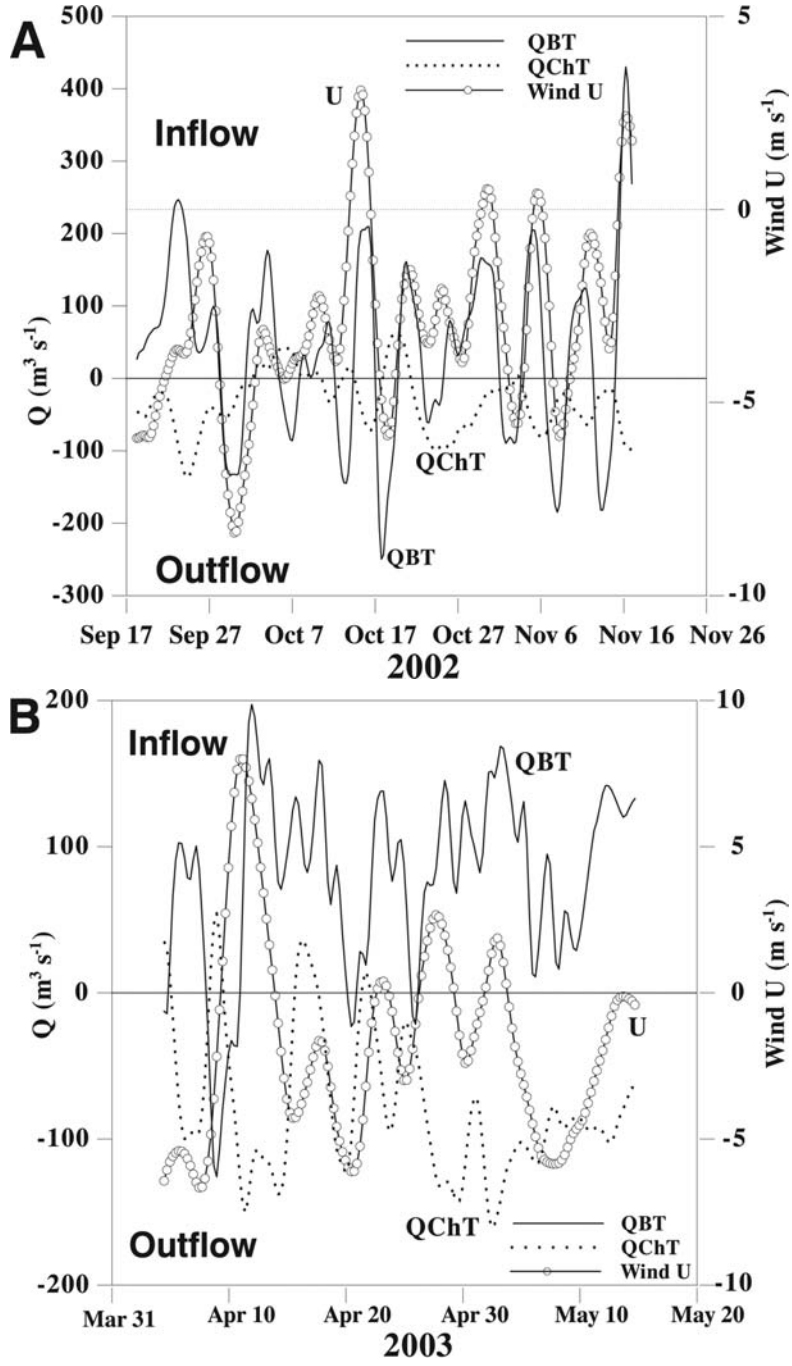

Figure 10 (A) Total flows to northeast basin over banks (QBT) and through channels (QChT) together with east-west winds (U) for wet season of 2002. (B) Total flows to northeast basin over banks (QBT) and through channels (QChT) together with east-west winds (U) for dry season of 2003.

maintains a much lower salinity due to its considerably larger positive net freshwater supply and greater mixing volume.

Wind-Induced Water Renewal and Residence Times.—Northeast basin average salinity increased over the seasonal time scale at a mean rate of 1.5 mo^{-1} between wet and dry seasons. Typically the increase in mean basin salinity over the dry season is considerably slower than the wet season decline, which was about –2.7 mo^{-1} for the northeast basin from Jul 2001 to Jan 2002 (Kelble et al., 2006). Somewhat surprisingly, the minimum salinity of the wet season of 2002 occurred in Jul, which is normally the end of the dry season with maximum salinity. Also mean salinity increased during the fall, a period when the largest decrease in salinity usually occurs. This reversal of the seasonal cycle of mean basin salinity is explained by the occurrence of an El Niño over the 2-yr period of 2002 and 2003. Kelble et al. (2006) showed that this El Niño disrupted the seasonal salinity cycle throughout Florida Bay by reversing the climatological wet and dry seasons, while decreasing the amplitude of the seasonal salinity change.

A large fraction of the freshwater delivered to the northeast basin during these El Niño years appears to be trapped within the basin with little exchange with surrounding waters, thus maintaining salinities considerably lower than other parts of Florida Bay. Determining the basins total volume exchange rate, Q_T, with adjacent waters and estimating residence times are difficult tasks requiring the integration of observational and modeling efforts. We applied a strategy of directly measuring the volume transports through the larger channels, Q_C, connecting to the basin and estimating the total change in basin mean volume over time from mean sea level variations, and then deriving the residual flow over the shallow banks and unmeasured channels, Q_B, from Eqn 1. The method was first used by Lee et al. (2006) to show that water renewal of the north-central subregion, where persistent hypersalinity occurs, is regulated by weak wind-driven throughflows with magnitudes of 11 and 3 $m^3 s^{-1}$ for dry and wet seasons of 2001 that require 6–12 mo to totally flush the basin. Similarly, for the northeast basin, wind-driven throughflows are the primary mechanism controlling renewal of basin interior waters. Strong cold front-driven winds toward the east and southeast during the winter/spring dry season cause a mean inflow over the western banks of the basin and mean outflow through the eastern channels of approximately 78 $m^3 s^{-1}$ that requires 2 mo to transport a volume equivalent to the basin mean volume. Using the surface area of the northeast basin we found that a throughflow of 1 $m^3 s^{-1}$ was equal to 0.88 cm mo^{-1} change in mean sea level, therefore a throughflow of 78 $m^3 s^{-1}$ would cause a mean sea level change of 68.6 cm mo^{-1} or 22.9 cm in 10 d, which is 15% of the mean basin volume (using a mean water depth of 150 cm and assuming constant surface area) and would require 67 d of steady flow to equal the mean volume of the basin. However, these throughflow events typically last from 5–10 d then reverse as the wind shifts westward. The net volume of water entering the basin consists of a mixture of the previously discharged basin water with a fraction of "new waters" that had not previously been within the basin. Field estimates using conservative dye tracers indicate that about 40% of inflows to shallow coastal lagoons can be considered "new waters". Using the 40% new water estimate reduces the effective dry season flushing rate to 31 $m^3 s^{-1}$ or 27.4 cm mo^{-1}, requiring approximately 5.5 mo to replace 100% of the mean basin volume. During the wet season, a mean throughflow of 33 $m^3 s^{-1}$ is estimated from the El Niño influenced eastward wind events that typically lasted for about 5 d and caused a net inflow over the banks

and net outflows through the channels. Assuming 40% of this flow is new water the effective flushing rate becomes 13.2 $m^3 s^{-1}$ or 11.6 cm mo^{-1} and requires almost 13 mo to completely renew the mean basin volume. Since the mean basin renewal times are longer than the seasonal time scales it is reasonable to assume a one year residence time for the northeast basin waters. Nuttle et al. (2000) estimated a 7 mo residence time for the northeast basin using an 8-yr salinity data set from Florida Bay for 1987 to 1995 to calibrate a salinity box model, and a mean depth for the northeast basin of 100 cm. Using our 150 cm mean depth, Nuttle et al.'s exchange flux would produce a residence time of 10.5 mo, which agrees closely with our estimate. Nuttle et al. (2000) also mentioned that it would take over a year for the waters of the eastern and central regions to be completely replaced by exchange flux.

If we assume that the wind-driven net throughflows are approximately zero when averaged over a season, we can equate the seasonal average total basin volume transport, Q_T, to the sum of the freshwater flux ($r + P + E$) plus groundwater, Q_g, as in Egn. 2 and Table 5, and thereby estimate the magnitude of groundwater inflow. For both the wet and dry seasons, we found that a weak groundwater outflow or downwelling of –1 to –2 $m^3 s^{-1}$ was required to complete the seasonal water balance. A similar groundwater outflow was previously found for Whipray Basin during the wet season using the same approach (Lee et al., 2006), while a weak inflow of about +1 $m^3 s^{-1}$ was estimated for the dry season. A negative groundwater flow could result from higher sea levels in the fall or from the negative freshwater flux that occurred in the northeast basin due to the larger runoff in the wet season and larger precipitation in the El Niño influenced dry season. Possibly during a normal dry season with positive freshwater flux there would have occurred a weak inflow of groundwater as occurred for Whipray Basin in 2001. However, negative groundwater flow has often been observed at the start of the wet season by the USGS at their Taylor River monitoring site upstream of Florida Bay (C. Hittle, USGS, pers. comm.). The uncertainty associated with the groundwater estimate is roughly approximated at ±3 $m^3 s^{-1}$ from a combined uncertainly of ±3 cm mo^{-1} for the seasonal average freshwater flux terms. This indicates that the magnitude of groundwater flux to the northeast basin is not significantly different from zero.

Conclusions

Water renewal within the northeast basin was found to be controlled by local wind forcing, similar to that found previously for Whipray Basin in the north-central subregion of Florida Bay. Zonal winds cause net inflows over the enclosing shallow banks and net outflows through connecting channels. The resulting mean throughflows can effectively replace the mean volume of the northeast basin with new water in approximately 6–12 mo. The long residence times of the basin, together with the basin's persistent low-salinity pattern, indicates that Everglades freshwater discharge to Florida Bay is primarily trapped within the northeast basin, with little direct influence on salinity of north-central subregion waters where hypersalinity routinely develops during dry seasons. However, salinity of north-central waters has been shown to respond more rapidly to freshwater runoff than in the northeast region where most of the runoff occurs. Therefore, it should be feasible to manage hypersalinity development within Florida Bay by diverting a relatively small portion of the Everglades flow during the dry season from Taylor Slough to McCormick Creek that dis-

charges to Whipray Basin in the north-central subregion. The flow diversion should occur upstream of the coastal mangrove lagoons that separate Florida Bay from the fresh water habitats of the Everglades. Seasonal water balance estimates indicate that groundwater discharge to Florida Bay is negligible.

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