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research paper

Circulation and water renewal of Florida Bay, USA

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ABSTRACT.—The circulation and exchange processes controlling transport and water renewal within the western subregion of Florida Bay, USA, are presented and compared to our previous findings for the north-central and northeast subregions of the bay. We find there is a common bank/basin flow response to wind forcing that is the primary driver of water renewal for each of the regions studied. Florida Bay is a patchwork of shallow basins surrounded by very shallow banks that are cut through with deeper channels connecting to nearby basins. We observed that, for each subregion studied, there was a net downwind basin outflow through the larger channels that was approximately balanced by a net basin inflow over the surrounding shallow banks. The resulting basin throughflows are used to estimate exchange times for renewal of western basin waters of approximately 1 mo. This exchange time is sufficient to prevent hypersalinity and degradation of water quality in the western basin, in contrast to the north-central subregion, where hypersalinity development is an annual occurrence. Our results highlight the importance of wind induced water renewal in shallow coastal bays with weak to moderate tidal exchange. In addition, we have discovered a significant clockwise circulation pattern through the western basins from strong inflows of coastal waters through Flamingo Channel that turn southward through the western basins before rejoining the coastal flow toward the Florida Keys tidal passages and Atlantic coastal zone. A practical solution to control hypersalinity, sea grass die-off, and water quality degradation of Florida Bay is proposed.

A major reconstruction project is underway in south Florida to restore freshwater flow into Florida Bay and Ten Thousand Islands to pre-development "quantity, quality, and timing" as per the Comprehensive Everglades Restoration Plan (CERP) being implemented under the Water Resources Development Act (WRDA 2000) and the Florida Forever Act (FFA 2000). One objective of CERP is to reduce hypersalinity (salinity > 40) within Florida Bay. Over the past decade, we have engaged in observational studies of the circulation and water renewal properties in three of the four major subregions of Florida Bay (Fig. 1). Our goal was to understand how circulation and exchange processes relate to hypersalinity development within the bay, and transport to downstream areas such as the Florida Keys National Marine Sanctuary (FKNMS). Our initial studies centered on the north-central subregion of the bay, which is characterized by weak water renewal and hypersalinity development during the dry season (Lee et al. 2006). Next, we focused on the northeast subregion, which receives a large fraction of the direct Everglades freshwater discharge to Florida Bay. This fresh water tends to be trapped within the northeastern part of the bay and has little apparent influence on containing hypersalinity development in the adjacent north-central subregion (Lee et al. 2008). In both the north-central and northeast subregions, we found that local winds were the primary forcing mechanism causing water renewal. However, net renewal rates were weak and resulted in residence times of about 1 yr. Similar findings have come from recent model studies of shallow coastal embayments with multiple interior basins on the Virginia coast (Safak et al. 2015) and for Mediterranean coastal bays (Umgiesser et al. 2014). Both these studies showed that the influence of wind forcing on interior basin water renewal becomes more important as the distance from ocean tidal inlets increases.

Here we concentrate on the western subregion of Florida Bay where there is exchange with the southeastward flow of the southwest Florida shelf (Lee and Smith 2002). By combining the results of net flow measurements through the three subregions of Florida Bay, we derived a clockwise wind-driven residual circulation pattern through the western interior portion of the bay with inflow through Flamingo Channel in the northwest section of the bay and outflows through Ninemile Bank and Twin Key Bank (Fig. 1). The eventual fate of these western bay waters will be the Atlantic coastal zone of the Florida Keys, due to the net Gulf of Mexico to Atlantic flow along the southwest Florida shelf and through the tidal channels of the middle and lower Florida Keys (Lee and Smith 2002).

Our goal was to better understand circulation and exchange processes within Florida Bay, as well as the bay's impact on surrounding waters of the Florida Keys and FKNMS. Seasonal development of hypersalinity within the central region of the bay, together with transport to nearby protected areas, leads to widespread water degradation and sea grass die-off. We present a practical engineering approach that would prevent hypersalinity from developing within Florida Bay.

Methods

Area of Study.—Florida Bay is the southernmost region of the Everglades National Park (ENP), located between the Florida mainland to the north, and the Florida Keys to the south (Fig. 1). This orientation creates a triangular shape made up by the wide (39 km) western bay boundary shared with the southwest Florida shelf, and the closed northeast corner of the bay where the Florida Keys merge with

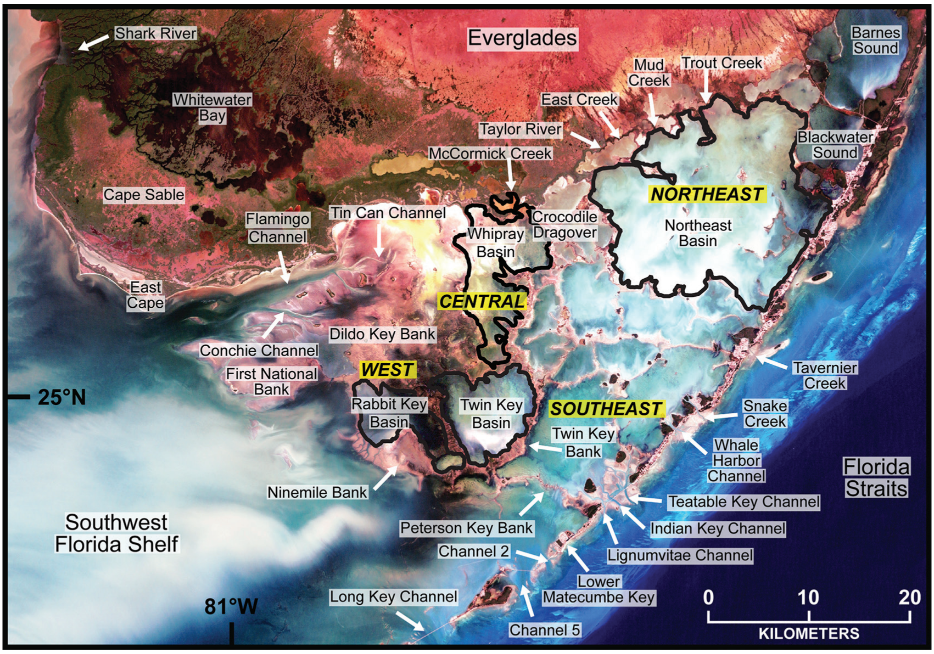

Figure 1. Aerial view of Florida Bay and the southern Everglades from a Landsat-7 extended thematic mapper image showing the shallow bank and basin configuration. Banks are shown by tan colors (depths <0.5 m) and basins with blue and green (depths approximately 1–2 m). The white areas appear to be due to sun glint. The bay's four subregions are identified as well as significant interior basins, western banks, and major freshwater discharge locations (rivers and creeks). Western ("West"), North-central ("Central"), and Northeast subregions are shown highlighted with a black border.

the mainland. The western boundary of the bay extends southeast from East Cape Sable to Lower Matecumbe Key. More than 75% of this western boundary is made up of wide, seagrass-covered shallow banks (First National Bank and Ninemile Bank) that join with the narrow Peterson Key Bank in the east (Fig. 1). The largest opening to the bay with the greatest tidal flow occurs through Flamingo Channel in the northwest, a 3-m deep channel that extends east to Flamingo between East Cape Sable and First National Bank. Conchie Channel branches off Flamingo Channel and provides flow to waters north and east of Dildo Key Bank. There is also a series of narrow tidal channels through Ninemile Bank providing flow access to Rabbit Key Basin, as well as small channels allowing flow through Peterson Key Bank to the southeast subregion of the bay. Freshwater flow from the Everglades enters Florida Bay through a series of small creeks that discharge into the northeast subregion of the bay. In addition, fresh water from the Shark River discharge can be transported around Cape Sable in a low-salinity plume and into Flamingo Channel (Lee et al. 2006, 2008, Kelble et al. 2007).

The interior of Florida Bay is made up of a patchwork of shallow basins with depths of 1–2 m and even shallower mud banks (<0.5 m; Fig. 1). Flow between basins occurs through narrow tidal channels and across the shallow banks (Lee et al. 2006, 2008). Tides along the western boundary of the bay are a mix of the diurnal tide of the Gulf of Mexico and the semi-diurnal tide of the Atlantic Ocean, and result in tidal range variations of 1.0–1.5 m with a 14-d period. The largest tidal range of 1.5 m occurs during spring tides in Flamingo Channel and decreases toward the Florida Keys. In the interior of the bay, there is a rapid fall-off of tidal range with distance from the western boundary. The tidal range becomes less than a few centimeters in the bay's northeast subregion, from dampening of the tidal wave by the shallow banks (Wang et al. 1994, Smith 1997). This decrease in water exchange by tides further increases the isolation of the interior basins and increases the importance of wind forcing on renewal of residual bay waters, similar to that shown by modeling studies by Safak et al. (2015) for the Virginia coast and Umgiesser et al. (2014) for the Mediterranean Sea. The more isolated the water body becomes due to distance or physical separation from the ocean connection by shoals or banks, the more important wind forcing becomes for renewing interior residual waters.

Based upon historical salinity records, the northeast subregion has the lowest salinities, primarily because it receives approximately 75% of the Everglades freshwater discharge, combined with weak interaction with adjacent regions (Lee et al. 2008). The north-central area has the highest salinities, due to a lack of Everglades freshwater input, weak water renewal rates, and shallow depths, all of which facilitate higher salinities through evaporation (Lee et al. 2006, Kelble et al. 2007). Both the north-central and northeast subregions have large seasonal salinity variability from poor exchange with adjacent waters, whereas the southeast and western subregions display smaller seasonal changes due to their greater tidal exchange with connecting coastal waters (Boyer et al. 1997, Nuttle et al. 2000, Kelble et al. 2007).

The south Florida climate consists primarily of two seasons, the wet season of summer/fall (June–November) and the dry season of winter/spring (December–May). During El Niño events, these seasons can reverse (Lee et al. 2008, Johns and Lee 2012). In all four subregions, the seasonal cycles of salinity tend to be in phase due to the large-scale climate control of south Florida's net freshwater cycle (Nuttle et al. 2000, Kelble et al. 2007). Maximum salinities of all subregions tend to occur in early summer (June and July) following the end of the dry season, when evaporation is at a maximum and freshwater input is low. Minimum salinities occur in December and January following the wet season, when evaporation is at a minimum and river runoff, which lags the wet season by approximately 1 mo, is strongest. The north-central portion of the bay typically becomes hypersaline during winter, spring, and early summer due to poor water exchange and lack of fresh water (Boyer et al. 1997, Fourqurean and Robblee 1999, Lee et al. 2006, Kelble et al. 2007).

Field Measurements.—Our observational strategy for the western subregion was similar to that previously used for the north-central and northeast subregions (Lee et al. 2006, 2008). It was designed to directly measure salinity variability and volume transports between western basins (Rabbit Key Basin and Twin Key Basin) and the connecting waters of Florida Bay and the southwest Florida shelf (Fig. 2). Currents, salinity, and temperature were continuously measured in flow channels connecting these basins with the surrounding waters over a 4.7-mo period during the wet season of 2004 (June 9–October 29) and a 5.7-mo period during the following dry season (December 3, 2004–May 25, 2005). For Rabbit Key Basin, moored current meters were deployed in the four larger channels through Ninemile Bank (Iron Pipe, Ned, Chlorox, and Y Channels), and also in Rabbit Key Channel that connects Rabbit and Twin Key Basins, and in Topsy Channel at the southern opening to Whipray Basin (Fig. 2).

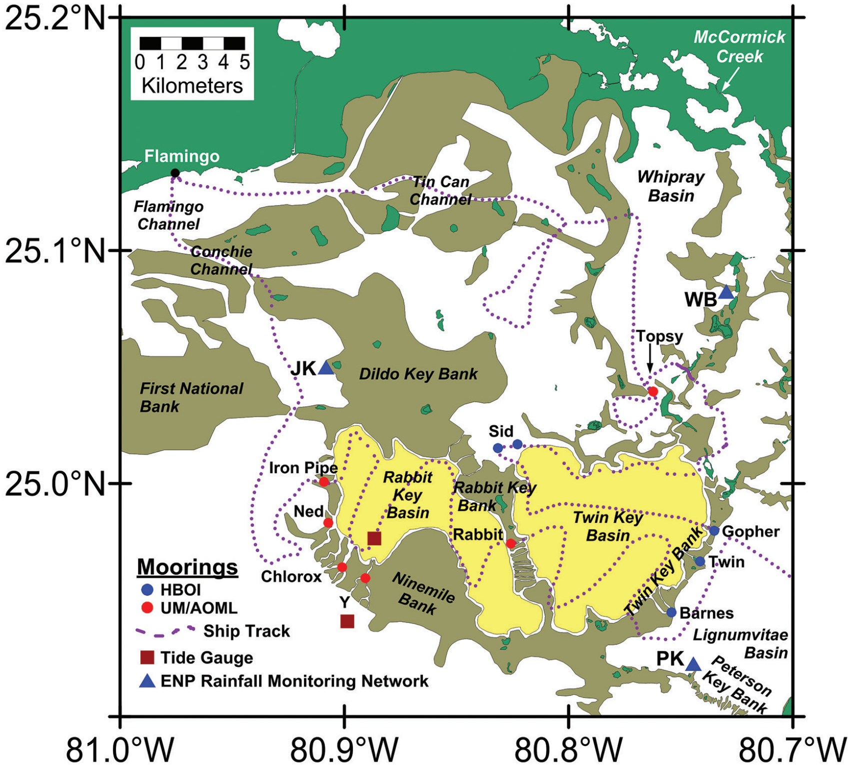

Figure 2. Moored instrument locations and shipboard survey track. Blue circles indicate Harbor Branch Oceanographic Institued (HBOI) moorings and red circles University of Miami/Atlantic Oceanographic and Meteorological Laboratory (UM/AOML) moorings. All moorings measured currents, temperature, and salinity. Acoustic Doppler Current Profiles (ADCP) transport transects were conducted across channels at all current meter sites. ENP rain gauge stations are shown by blue triangles. Red squares indicate UM/AOML tide gauge locations. Yellow areas represent the western subregion of Rabbit Key and Twin Key basins with depths ranging from 1 to 2 m. Brown areas identify shallow banks with depths <0.5 m. White areas inside the bay typically have depths ranging from 0.5 to 1 m. Flamingo and Conchie Channels have depths ranging from 2 to 3 m.

Currents were measured with Sontek Argonaut SL (side-looking) and MD (upward looking) acoustic current meters that averaged currents at mid-depth over a horizontal distance of 2–3 m from the transducers and with a sampling interval of 10 min. Each current meter was also equipped with a SeaBird SBE 37 MicroCat conductivity and temperature recorder set to a 10 min sampling interval. Sea level variability inside Rabbit Key Basin and west of Ninemile Bank in southwest Florida shelf waters was measured with SeaCAT bottom pressure recorders with 30 min sampling intervals. Together, these two instruments provide the slope of sea level across Ninemile Bank. The bottom recorders also measured conductivity and temperature. All Rabbit Key Basin measurement sites had nearly complete data returns, with the exception of the Rabbit Key Channel current meter that had a 19-d data gap during the wet season from July 29 to August 17, and failed after 2 mo of data collection during the dry season. The 19-d data gap in the low-frequency time series was filled using a least-square linear regression on the east-west winds, which were highly correlated with subtidal transports through Rabbit Key Channel (R^2 = 0.80).

For Twin Key Basin, moored current meters equipped with salinity and temperature sensors were deployed in three of the larger channels that connect Twin Key Basin to Lignumvitae Basin in the southeast subregion (Fig. 2). Two additional current meters were deployed in the northern part of Twin Key Basin between Sid Key and Rabbit Key. Study sites in Barnes Key Channel (designated Barnes, Fig. 2), Gopher Keys Channel (Gopher), South Twin Keys Channel (Twin), and between Rabbit Key and Sid Key (Sid) were instrumented using Sontek Argonauts or General Oceanics Mark II inclinometers for current measurement and Falmouth Scientific, Inc. pressure sensors at mid-depth for water depth measurement. All current and pressure measurements were made hourly.

Missing current meter data from South Twin Keys Channel and from Gopher Keys Channel during the wet season study were replaced using multiple linear regression analysis (Eisensmith 1985). Flow through South Twin Keys Channel was estimated using current data from Gopher Keys Channel and Barnes Key Channel as predictors (R^2 = 0.995), and flow through Gopher Keys Channel was estimated using currents from Barnes Key Channel and South Twin Keys Channel as predictors (R^2 = 0.958). Current and pressure data records between Rabbit Key and Sid Key were complete for both study periods.

Measured currents were converted to along-channel volume transport time series for all 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 4 to 6 consecutive transects per channel. Each transect took 1–2 min to complete, resulting in ensemble-averaged transports over 4–12 min. The only exception was at the 0.74 km wide Sid transect in Twin Key Basin, where each transect took 14–15 min to complete and the average transport was computed for each single transect. 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 current meter measurements of along-channel currents averaged over the same time intervals as the vessel transects. There was a total of 10 d of shipboard calibrations of channel transport at current meter sites over the two seasons, with 4 to 6 ensemble averaged transport sections at each site per day. Therefore, the total number of transport sections per current meter site ranged from 40 to 60 over the study period. During both seasons, shipboard transports were found to be highly correlated with the moored current measurements, accounting for 80%–99% of the measured variance of currents. The only exception was for Rabbit Key Channel during the wet season when only 44% of the measured current variance was associated with the shipboard transports, possibly due to the aforementioned gap in the data record. During the dry season, Rabbit Key Channel results were similar to those in the other channels.

Everglades freshwater discharge to Florida Bay and the Ten Thousand Islands region west of Florida Bay was measured by the United States Geological Survey (USGS) using ADCP vertical current profiles calibrated with shipboard ADCP volume transports to derive discharge time series. 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). Precipitation in the vicinity of the western bay was measured by three rain gauges maintained by the ENP (Fig. 2). Local wind time series were obtained from Coastal Marine Automated Network and SeaKeys monitoring stations in the Florida Keys and northwest Florida Bay. All wind data are presented as east–west (U) and north–south (V) components, where +U represents wind toward the east (−U toward west) and +V is toward the north (−V toward south). Regional scale winds are observed to be highly coherent over the study area (Lee and Williams 1999). We consider the winds from the Sombrero Reef CMAN station located east of Marathon (not shown) to be representative of the region.

All time series data were first smoothed with a 3 Hour Low-Pass (HLP) filter to remove high frequency noise, then filtered with a 40 HLP Lanczos filter to remove tidal and sea breeze influences, and to more clearly resolve low-frequency (subtidal) changes following standard filtering techniques (Press et al. 1992).

Salinity surveys of the western basins were made approximately every 2 wk throughout the wet and dry seasons using a flow-through system incorporating a SeaBird 21 thermosalinograph with an intake at about 0.5 m mounted on the bow of the R/V Virginia K. Given the shallow water depths and well-mixed water column, sampling at this depth is considered representative of the entire water column. Surveys were begun at Flamingo Marina in Flamingo Channel and extended east through the north-central subregion, then south through Twin Key and Rabbit Key Basins, with return to Flamingo through Conchie Channel (Fig. 2). The vessel survey speed was kept nearly constant at approximately 10 m s^{-1}. Given the 7-s sampling interval, this resulted in a spatial resolution of about 70 m. It generally took <3 hrs to complete a detailed survey of the western basins and adjacent regions (Fig. 2). Synoptic salinity surveys were also conducted monthly over all of Florida Bay using the same vessel and instrumentation (Kelble et al. 2007). Each of these bay-wide surveys took 2 d to complete. Contoured salinity maps were produced from gridded fields of each salinity survey using optimal interpolation procedures with Golden Software's Surfer program (Figs. 3, 4). Spatially-averaged salinity values for Rabbit Key and Twin Key Basins were computed for each survey.

The interior basins of Florida Bay are interconnected by flow over the surrounding banks and through the bank channels. Direct measurement of water exchange between basins is impractical due to the shallow depths and large areal extent of the banks. Therefore, we applied the method of Lee et al. (2006) to develop a time series of the volume changes of Rabbit Key Basin, $\partial V_{RB}/\partial t$, from measured variations of sea level and the basin's surface area. The total flow, Q_T, into or out of this western basin must balance the sum of the flows through the measured channels in Ninemile Bank and Rabbit Key Bank, Q_c, plus the flows over the surrounding shallow banks and any small channels that were not measured, Q_b, written as:

$$\partial V_{RB}/\partial t = Q_T = Q_c + Q_b \quad \text{(Eq. 1)}$$

Sea level fluctuations were measured with bottom pressure stations located in the interior of Rabbit Key Basin and south of Ninemile Bank on the southwest Florida shelf (Fig. 2). The Rabbit Key Basin gauge was used to estimate a time series of mean basin sea level changes, which when multiplied by the basin surface area and demeaned, provides a time series of basin total volume anomaly, $\partial V/\partial t$, which must balance the basin's total flow, Q_T. ArcView software was used to calculate the basin

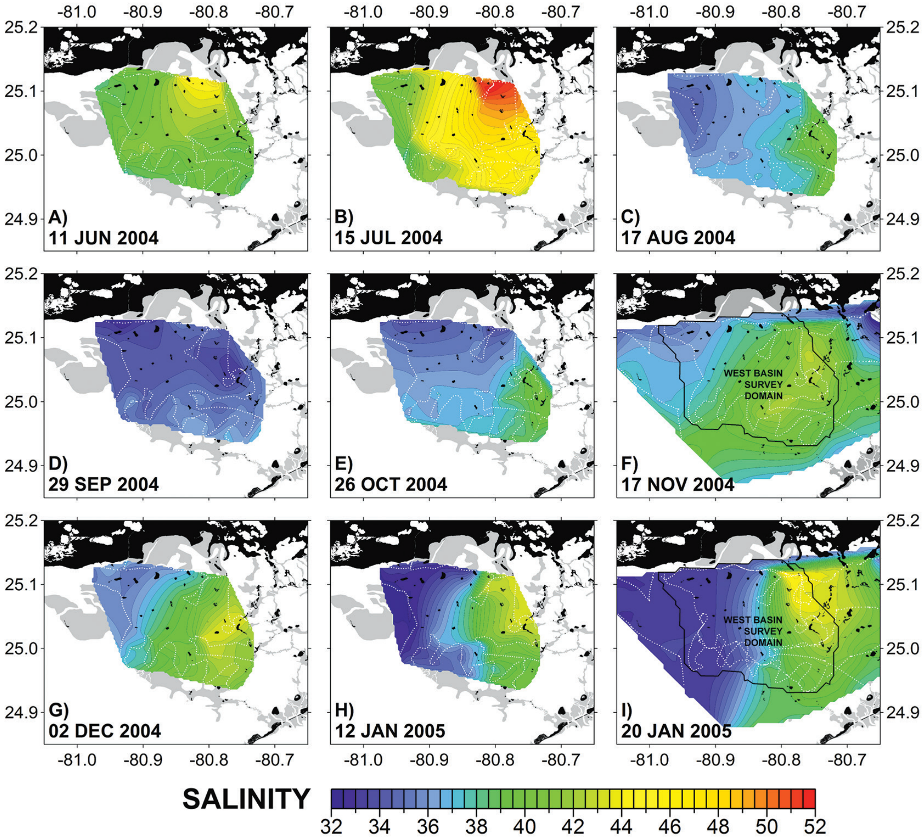

Figure 3. Surface salinity of western and central regions of Florida Bay from surveys of the R/V Virginia K using continuous underway measurements for the period from June 15, 2004 to January 20, 2005. Vessel track is shown with white dotted lines. The *y*-axis is north latitude and *x*-axis is west longitude.

surface area as the area within the outer perimeter of the basin, which traces the inside edges of the banks so as not to include the surrounding banks. Mean depths were also computed from ArcView software by averaging the basin mean sea level bathymetric data. Equation 1 was used to estimate the combined flow over banks and through ungauged channels (Q_b), thus providing an estimate of total basin flow (Q_T).

Results

Salinity.—Surface salinity spatial patterns from the R/V Virginia K surveys are shown in Figures 3 and 4 for the period from June 11, 2004, to July 12, 2005. To better understand the variability of these salinity patterns, we plotted time series of basin average salinity together with total daily average freshwater discharge to Florida Bay and the Ten Thousand Islands together with daily average precipitation from the three rain gauges located in western Florida Bay (Fig. 5). Freshwater flow to the Ten Thousand Islands is computed as the combined Everglades discharge through Shark, Broad, Harney, and Lostmans rivers. River locations are shown in Figure 6, along with the large-scale salinity distribution of south Florida coastal and bay waters for February 2005. Total freshwater flow to Florida Bay is estimated from the

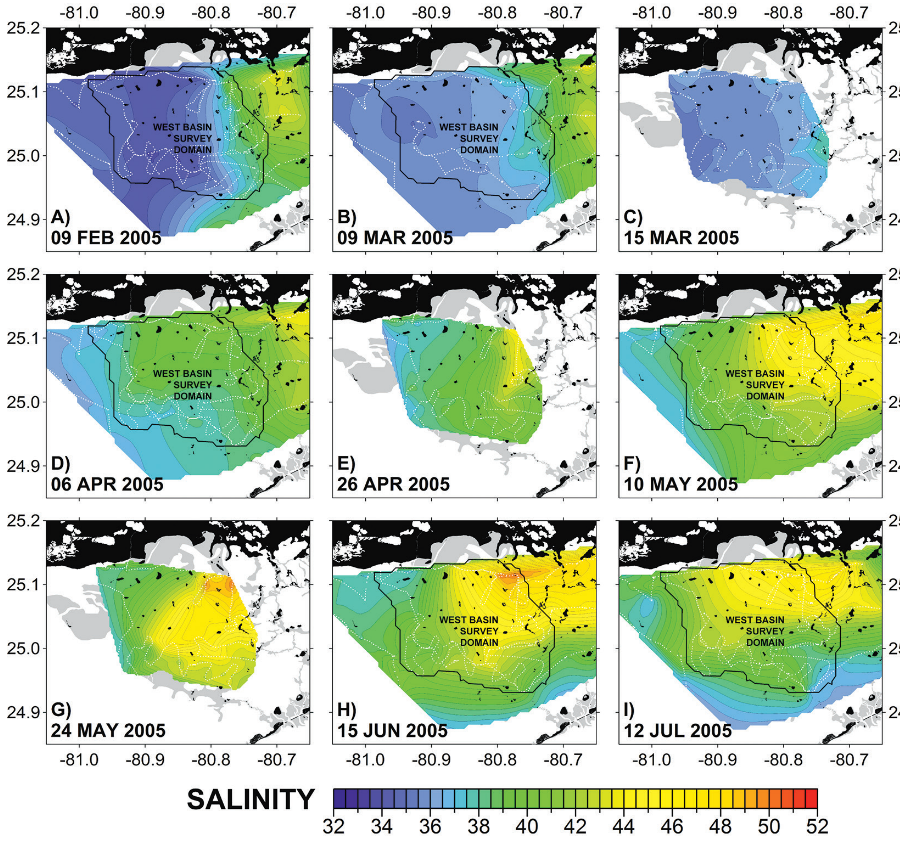

Figure 4. Surface salinity of western and central regions of Florida Bay from surveys of the R/V Virginia K using continuous underway measurements for the period from February 9 to July 12, 2005. Vessel track is shown with white dotted lines. The *y*-axis is north latitude and *x*-axis is west longitude.

combined flows through Taylor River, Mud Creek, and Trout Creek located in the northeast subregion of the bay (Fig. 1). These three creeks transport approximately 85% of the total Everglades flow (approximatley 25 $m^3 s^{-1}$) to the bay (Lee et al. 2008). The remaining 15% discharges through East Creek, which was not instrumented for discharge measurement during our study. Direct river discharge to Florida Bay averaged 10 $m^3 s^{-1}$ (Fig. 5) from August 1 to November 30, 2004, during the wet season, whereas the mean discharge to Ten Thousand Islands was a factor of 10 larger at 103 $m^3 s^{-1}$. For the dry season period from December 1, 2004, to March 31, 2005, the average freshwater discharge to Ten Thousand Islands decreased to 34 $m^3 s^{-1}$, and direct discharge to Florida Bay was negligible at 1 $m^3 s^{-1}$.

Western basin salinity surveys toward the end of the 2004 dry season in June and July illustrate this lack of freshwater input, with hypersalinity peaking at >50 in the bay's north-central subregion, and western basin average salinity was >40 (Figs. 3 and 5, respectively). The start of the 2004 wet season was delayed until mid-July when rainfall over the Everglades and Florida Bay began to increase, followed by a rapid decline in salinity throughout the bay (Figs. 3, 5). However, this freshening of the bay was short-lived as the wet season ended abruptly in October and the subsequent dry season continued until June 2005. Salinities of the western and north-central

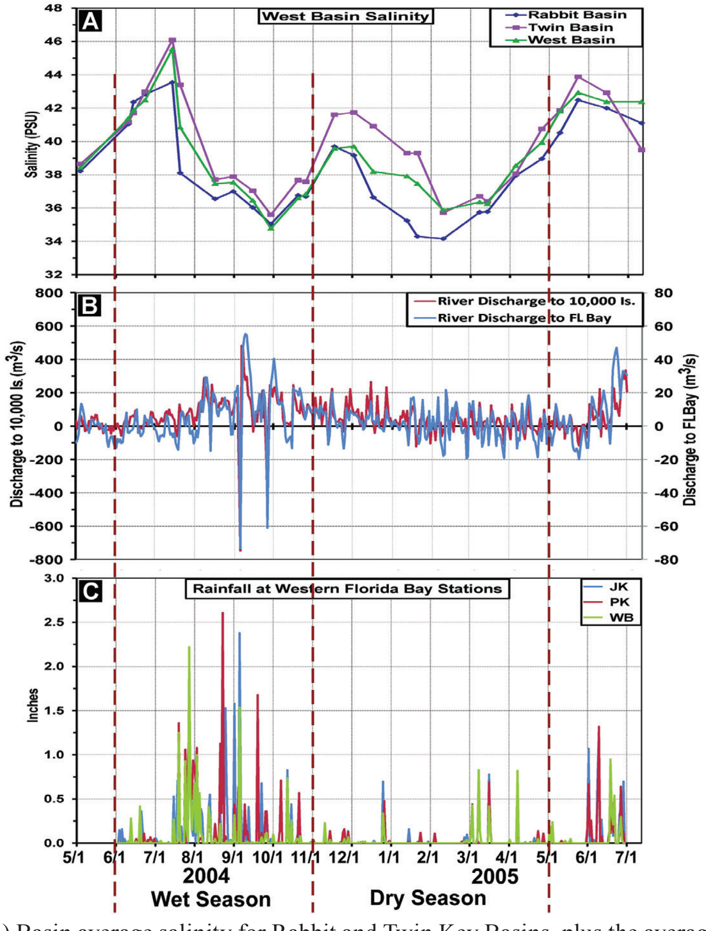

Figure 5. (A) Basin average salinity for Rabbit and Twin Key Basins, plus the average of the two basins representing the western basin subregion for the period May 2004–July 2005. (B) Daily averaged river discharge to Florida Bay and to Ten Thousand Islands. (C) Daily average rainfall measured near the western subregion at Johnson Key (JK), Peterson Key (PK), and Whipray Basin (WB) by Everglades National Park.

bay subregions began increasing immediately in response to the onset of the dry season, but then ended abruptly as a freshening event began at the end of November that continued until mid-February 2005. This freshening was not associated with increases in either local rainfall or Everglades discharge into Florida Bay. Western bay waters continued to show lower salinities than expected for the dry season until mid-March 2005, when salinities again began to rise and peaked above 40 by the end of the dry season in the latter part of May, commensurate with the onset of the 2005 rainy season (Figs. 4, 5). However, salinities in the north-central subregion remained approximatley 40 throughout the winter low-salinity intrusion event, resulting in a large east-west salinity gradient across the shallow bank separating the central and western subregions. The salinity of Rabbit Key Basin was also consistently lower than in Twin Key Basin (Figs. 3–5). Twin Key Basin receives some higher salinity water from the north-central subregion, as well as interacts with the southeast subregion, where salinities remain close to those of Florida Keys Atlantic coastal zone waters due to tidal exchange (Nuttle et al. 2000, Lee et al. 2006, 2008).

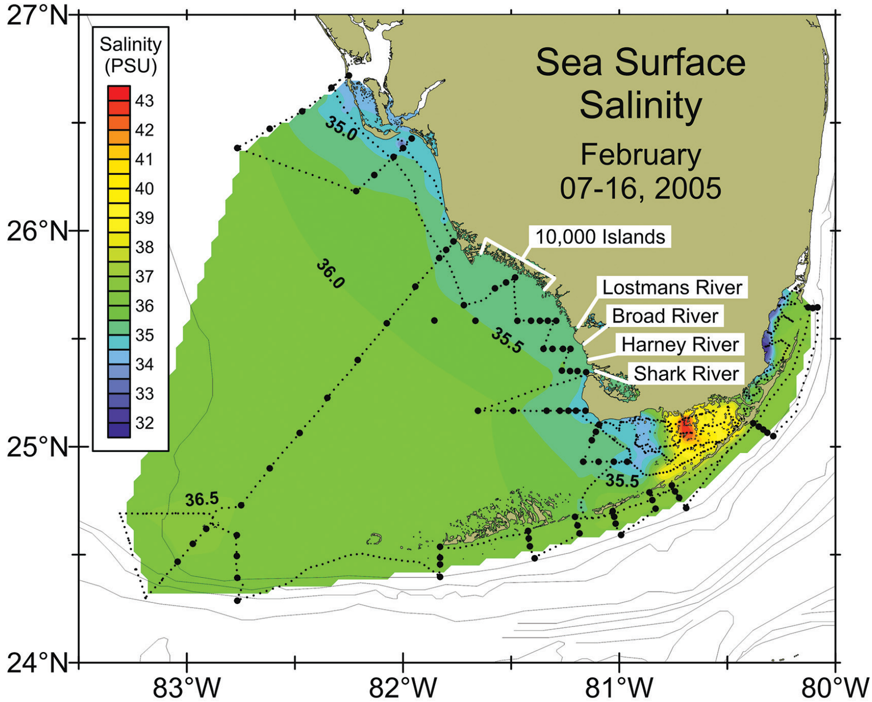

Figure 6. Surface salinity for the south Florida coastal region including Florida Bay and Biscayne Bay for the period February 7–16, 2005, from survey measurements of the R/V Walton Smith through the Atlantic coastal waters of the Florida Keys and southwest Florida shelf, combined with salinity surveys of Florida Bay and Biscayne Bay conducted by the R/V Virginia K. Charlotte Harbor is at the northern extent of the survey. Refer to the NOAA/AOML, South Florida Program web site (http://www.aoml.noaa.gov/sfp).

Transports.—First-order statistics of the 3 HLP and 40 HLP filtered wind components and volume transport time series derived for the measured channels connecting the western basins to adjacent regions are given in Table 1 and for both wet (1A) and dry (1B) seasons. The strongest tidal transport occurred at Ninemile Bank, which connects directly to the Gulf of Mexico, where the tidal range is >1 m. Standard deviations of the 3 HLP transports ranged from 6.2 to 316.1 $m^3 s^{-1}$ over both seasons, with the Sid section in Twin Key Basin having the largest flows due to its much greater width (Tables 1, 2). Typically outflows were larger than inflows for most channels except for Sid, which had a mean inflow of 98 $m^3 s^{-1}$ over the wet season and 12 $m^3 s^{-1}$ for the dry season. Volume transport through the Ninemile Bank Channels varied from nearly 100 to >500 $m^3 s^{-1}$, with the greatest transport through the largest channel, Chlorox (Tables 1, 2). Tidal currents through the Ninemile Bank Channels accounted for 96%–98% of the total transport variability as estimated from the percent of the variance due to high-frequency processes (periods <40 hrs). At Twin Key Channel 80%–85% of the transport variability was due to tidal currents. Standard deviations of 3 HLP transports were similar for Twin Key and Gopher Channels (between 30 to 40 $m^3 s^{-1}$) and somewhat smaller for Barnes Channel (6 to 10 $m^3 s^{-1}$). Volume transport variability in the western basin channels was primarily driven by tides in the Gulf of Mexico and Atlantic Ocean.

Flow variability through channels within the interior of Florida Bay shows a decrease in tidal influence with a corresponding increase in the influence of subtidal

Table 1. First order statistics of 3 Hour Low-Pass (HLP) along-channel transports (Q m^3 s^{-1}) within flow channels connecting western and central basins of Florida Bay, together with U (east–west) and V (north–south) wind components (Wind U and Wind V; m s^{-1}) over record periods of 2004 wet season and 2005 dry season. Inflows to basins are designated by positive transports and outflows by negative transports. See Figure 2 for site locations. n = number of data points, Perc high-freq = percent of variance that was high-frequency.

	Start (m/d/hr)	End (m/d/hr)	n	Mean	SD	Max	Min	Range	Variance	Perc high-freq
(A) Wet season 2004 (3 HLP 1-hr interval data)										
Wind U	6/11/18:00	10/26/18:00	3,289	−2.2	4.5	19.6	−13.7	33.3	20.2	7.5
Wind V	6/11/18:00	10/26/18:00	3,289	1.2	3.6	17.8	−13.6	31.4	13.0	24.2
Iron Pipe	6/11/18:00	10/26/18:00	3,289	1.2	40.7	95.8	−69.4	165.2	1,660.3	96.3
Ned	6/11/18:00	10/26/18:00	3,289	−6.1	38.1	93.4	−116.9	210.3	1,453.2	98.1
Chlorox	6/11/18:00	10/26/18:00	3,289	−22.9	147.2	235.5	−260.9	496.4	21,680.9	98.3
Y	6/11/18:00	10/26/18:00	3,289	−16.8	67.8	118.6	−120.0	238.6	4,603.0	98.1
Rabbit	6/11/18:00	10/26/18:00	2,835	13.2	18.2	45.9	−46.3	92.2	332.2	80.5
Topsy	6/11/18:00	10/26/18:00	3,289	−3.8	23.6	91.1	−63.1	154.2	558.2	71.5
Barnes	6/22/13:00	11/1/ 5:00	3,161	−1.0	10.1	29.5	−32.0	61.4	101.2	88.1
Twin	6/22/13:00	11/1/ 5:00	3,161	−9.3	35.5	62.4	−81.7	144.1	1,256.0	85.4
Gopher	6/22/13:00	11/1/ 5:00	3,161	−5.2	30.7	70.7	−88.2	158.9	942.3	82.2
Sid	6/22/13:00	11/1/ 5:00	3,161	97.8	316.1	1,418.3	−974.2	2,392.5	99,898.8	36.7
(B) Dry season 2005 (3 HLP 1-hr interval data)										
Wind U	12/3/00:00	5/25/00:00	4,153	−2.2	5.2	15.8	−14.7	30.5	27.2	13.0
Wind V	12/3/00:00	5/25/00:00	4,153	−0.8	4.7	15.4	−14.1	29.5	22.1	22.6
Iron Pipe	12/3/00:00	5/25/00:00	4,153	−4.0	38.1	73.2	−76.0	149.3	1,453.1	97.8
Ned	12/3/00:00	5/25/00:00	4,153	−7.9	50.1	96.2	−119.3	215.4	2,509.4	97.7
Chlorox	12/3/00:00	5/25/00:00	4,153	−1.1	157.0	286.6	−273.1	559.6	24,651.0	98.3
Y	12/3/00:00	5/25/00:00	4,153	0.1	78.8	162.6	−127.4	290.0	6,214.9	97.7
Rabbit	12/3/00:00	2/12/10:00	1,711	0.3	31.8	72.3	−49.4	121.7	1,009.8	86.5
Topsy	12/3/00:00	5/25/00:00	4,153	−2.5	27.2	81.3	−80.2	161.5	737.3	70.1
Barnes	12/14/11:00	5/17/11:00	3,697	1.6	6.2	18.8	−18.1	36.9	38.3	84.1
Twin	12/14/12:00	5/17/10:00	3,695	−10.9	41.2	68.1	−102.0	170.1	1,694.7	82.2
Gopher	12/14/13:00	5/17/9:00	3,693	−5.0	30.0	64.4	−79.0	143.4	902.3	79.3
Sid	12/14/12:00	5/17/8:00	3,693	12.0	118.3	457.6	−254.2	711.8	13,998.8	33.3

Table 2. First order statistics of 40 Hour Low-Pass (HLP) along-channel transports (Q m^3 s^{-1}) within flow channels connecting western and central basins of Florida Bay, together with U (east–west) and V (north–south) wind components (Wind U and Wind V; m s^{-1}) over record periods of 2004 wet season and 2005 dry season. Inflows to basins are designated by positive transports and outflows by negative transports. See Figure 2 for site locations. n = number of data points, Perc high-freq = percent of variance that was high-frequency.

	Start (m/d/hr)	End (m/d/hr)	*n*	Mean	SD	Max	Min	Range	Variance	Perc high-freq
(A) Wet season 2004 (40 HLP 6-hr interval data)										
Wind U	6/11/18:00	10/26/18:00	549	−2.2	4.2	17.5	−11.4	28.9	18.0	92.5
Wind V	6/11/18:00	10/26/18:00	549	1.2	3.2	13.9	−9.2	23.1	10.0	75.8
Iron Pipe	6/11/18:00	10/26/18:00	549	1.3	7.8	60.3	−19.4	79.7	61.1	3.7
Ned	6/11/18:00	10/26/18:00	549	−6.1	5.2	12.9	−24.7	37.6	27.2	1.9
Chlorox	6/11/18:00	10/26/18:00	549	−22.8	19.0	100.5	−78.6	179.1	361.5	1.7
Y	6/11/18:00	10/26/18:00	549	−16.8	9.2	40.4	−53.5	93.9	85.3	1.9
Rabbit	6/11/18:00	10/26/18:00	549	12.4	8.1	35.7	−37.7	73.4	65.8	19.5
Topsy	6/11/18:00	10/26/18:00	549	−3.7	12.8	67.9	−53.5	121.4	163.5	28.5
Barnes	6/22/13:00	11/1/ 5:00	528	−1.0	3.5	11.3	−15.9	27.2	12.0	11.9
Twin	6/22/13:00	11/1/ 5:00	528	−9.3	13.5	38.6	−62.1	100.7	183.0	14.6
Gopher	6/22/13:00	11/1/ 5:00	528	−5.2	0.2	41.8	−75.6	117.5	168.1	17.8
Sid	6/22/13:00	11/1/ 5:00	528	98.0	251.6	1,203.9	−734.7	1,938.6	63,328.9	63.3
(B) Dry season 2005 (40 HLP 6-hr interval data)										
Wind U	12/3/00:00	5/25/00:00	693	−2.2	4.9	10.1	−12.3	22.4	23.7	87.0
Wind V	12/3/00:00	5/25/00:00	693	−0.8	4.2	9.9	−12.4	22.4	17.4	77.4
Iron Pipe	12/3/00:00	5/25/00:00	693	−4.0	5.7	41.9	−21.1	63.0	32.0	2.2
Ned	12/3/00:00	5/25/00:00	693	−7.9	7.7	50.7	−34.8	85.4	58.7	2.3
Chlorox	12/3/00:00	5/25/00:00	693	−0.9	20.5	152.9	−73.5	226.4	419.6	1.7
Y	12/3/00:00	5/25/00:00	693	0.2	12.0	95.3	−41.2	136.5	144.2	2.3
Rabbit	12/3/00:00	2/12/10:00	286	0.3	11.6	40.5	−28.6	69.1	133.7	13.5
Topsy	12/3/00:00	5/25/00:00	693	−2.6	15.0	40.6	−50.7	91.3	225.7	29.9
Barnes	12/14/11:00	5/17/11:00	616	1.6	2.5	6.4	−10.2	16.5	6.1	15.9
Twin	12/14/12:00	5/17/10:00	616	−10.9	17.4	31.0	−69.0	100.0	302.5	17.8
Gopher	12/14/13:00	5/17/9:00	616	−0.8	13.7	29.2	−51.8	81.0	186.6	20.7
Sid	12/14/12:00	5/17/8:00	616	11.9	96.6	303.0	−186.0	489.0	9,337.9	66.7

processes (Table 2). Rabbit and Topsy Channels show that 13.5% to 29.9% of the total variance was due to low-frequency transports, and the Sid interior section of Twin Key Basin shows that approximately 65% of the transport variability was due to subtidal currents. Magnitudes of tidal transports decreased with distance from the open southwest Florida shelf, similar to Wang et al. (1994) observation for tidal range.

Subtidal volume transport time series from channels through Ninemile Bank, Rabbit Key Bank, and Topsy Key Bank are shown in Figures 7A and 8A along with east–west (U) and north–south (V) wind components for the wet and dry seasons, respectively. Positive transport values represent flows into Rabbit and Twin Key Basins for all channels except for Rabbit Key Channel, where positive transports represent inflow to Rabbit Key Basin and outflow from Twin Key Basin. Figures 7B and 8B expand 52-d time periods of the total measured flows through Ninemile Bank, Twin Key Bank, and the Sid section across the northern end of Twin Key Basin for better understanding of transport pathways and variability associated with local winds.

During the summer/fall wet season, winds over the south Florida region were primarily from the east and southeast (U/V mean values, Table 2), causing persistent low-frequency inflows to Rabbit Key Basin from the east through Rabbit Key Bank and compensating outflows to the southwest Florida shelf through Ninemile Bank (Fig. 7A). Subtidal transport fluctuations through the channels of Ninemile Bank were highly coherent and in-phase, but generally out of phase with transports through Rabbit Key Bank and in-phase with flow through Topsy Channel. The wet season expansion of the sum of channel transports through Ninemile Bank, plotted with the sum of transports through channels of Twin Key Bank and transports through the Sid section, together with U/V wind components, indicates a flow response to local wind forcing, which is coherent over the spatial scale of Florida Bay (Fig. 7B). The time period was chosen to show the transport response to typical summer winds from the southeast over 10 d in August, and the influence of the westward passage of two hurricanes (Frances and Jeanne) around September 5 and 26, 2004, followed by characteristic fall winds from the northeast with increased wind speeds. It is clear from this plot that flow through the wide Sid section is strongly dependent on the east-west wind component. Winds toward the east and southeast generally produce the largest Sid inflows and westward winds typically result in outflows. Also apparent is that subtidal flows through Twin Key Bank are out of phase with Sid transports, i.e., inflows through Sid correspond to outflows through Twin Key Bank and vice-versa. Flows through Ninemile Bank also appear to be positively correlated with the east-west winds ($R^2 = 0.33$) with westward winds associated with Ninemile Bank outflows and eastward winds with inflows. The strongest non-hurricane related outflows through Ninemile Bank were associated with stronger winds toward the southwest that occur regularly during the fall.

The only significant deviation from this summer basin-flow pattern was associated with the passage of hurricanes Frances and Jeanne on September 5 and 26, 2004, both of which moved westward across the state just north of Lake Okeechobee. The hurricanes caused a sharp increase in wind speeds over Florida Bay from 5 to about 15 m s^{-1}, with a cyclonic rotation toward the west then south, followed by eastward and then northeastward winds. Channel transports are seen to be strongly connected to these wind shifts (Fig. 7B). Flow through Ninemile Bank followed the east-west winds of the hurricanes very closely, with peak outflows occurring simultaneously with peak westward winds at the onset of the storms and large peak inflows

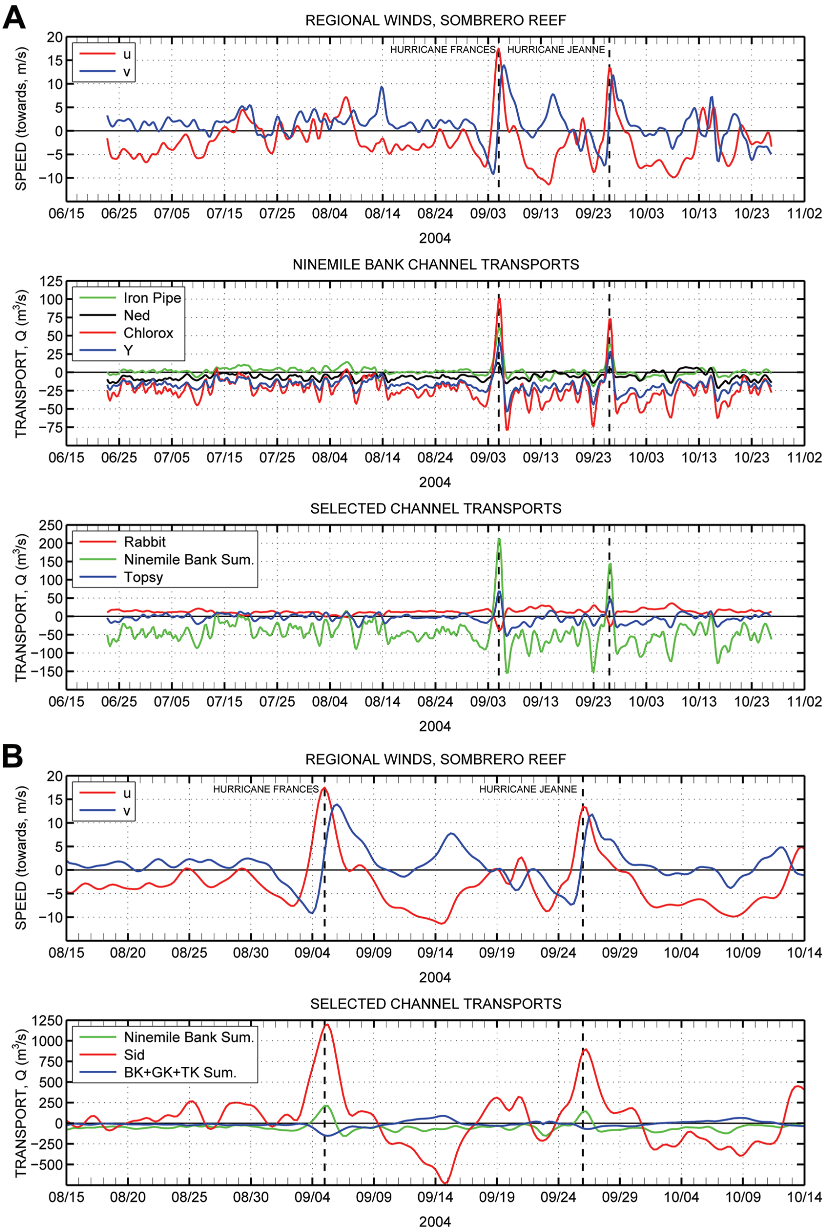

Figure 7. (A) Subtidal [40 Hour Low-Pass (HLP)] time series of east-west (U) and north–south (V) wind components from Sombrero Reef CMAN station (top panel), together with volume transports derived for the major flow channels to Rabbit Key Basin through Ninemile Bank for the wet season 2004 (mid panel) where positive values are inflows to the basin and negative are outflows. Bottom panel shows the transport sum through Ninemile Bank Channels plus transports through Rabbit Key Channel at the east side of Rabbit Key Basin and Topsy Channel located at the southern end of Whipray Basin where negative transport represents flow out of Whipray Basin and toward Rabbit Key Basin. (B) Blow-up of the sum of western basin transports (40 HLP) through Ninemile Bank, Sid section across northern Twin Key Basin, and Twin Key Bank (sum of flow through Barnes Key Channel (BK), Gopher Key Channel (GK) and Twin Key Channel (TK), shown as BK+GK+TK) plotted together with U and V winds for the wet season, 2004. Positive transports represents inflows for both Rabbit Key and Twin Key Basins.

occurring with peak eastward and northeastward winds as the storms moved across the state (Fig. 7A,B).

Absent hurricanes, South Florida winds during the winter/spring dry season are typically stronger and more variable than during the wet season due to the frequent passage of winter cold fronts (Johns and Lee 2012). These frontal events cause a clockwise rotation in local winds with an increase in wind speeds toward the northeast ahead of the front, shifting toward the east at the front, then southeast and south at speeds of 10 m s^{-1} or greater behind the cold front (Fig. 8A,B).

This characteristic pattern of local wind shifts during cold front passages produces clear and predictable responses in bank and basin transports, as shown in the enlargement of the dry season data (Fig. 8B). Northward winds at the start of an approaching cold front are accompanied by inflows to Rabbit Basin through Ninemile Bank Channels, switching to inflows to Twin Key Basin through the Sid section and outflow through Twin Keys Channel as the wind shifts toward the east. Next, as the wind rotates toward the southeast and south, the inflow to Twin Key Basin begins to decrease and outflows occur through Ninemile Bank Channels. As the wind continues to shift toward the southwest and west, flows in Rabbit Basin and Twin Key Basin reverse to become outflows through Ninemile Bank and the Sid section and inflow through Twin Key Bank. The end of the cold front passage is signaled by decreasing wind speeds toward the west and northwest. This pattern of wind-forced transports is repeatable as shown in Figures 8A and 8B, but many variations can occur due to changes in the strength and duration of the rotating wind vectors.

Seasonal mean flows for both Ninemile and Twin Key Banks and the large Sid section across the northern opening to Twin Key Basin are given in Table 3. Mean outflows (negative transports) were observed at Ninemile Bank and Twin Key Bank during wet and dry seasons, resulting in seasonal and annual mean outflows through both banks. The net outflow through Ninemile Bank was −44 m^3 s^{-1} for the wet season and −12.6 m^3 s^{-1} for the dry season, for an annual mean outflow of −28 m^3 s^{-1}. For Twin Key Bank mean outflows were similar for both seasons at nearly −15 m^3 s^{-1}, which is close to balancing the 12 m^3 s^{-1} inflow to Twin Key Basin through the Sid section during the dry season. Over the wet season there was a large mean inflow to Twin Key Basin of 98 m^3 s^{-1} that was not balanced by the total measured bank outflows through Twin and Ninemile Banks of −60 m^3 s^{-1} (Table 3).

Water Balance.—Using Equation 1 we compute the unknown flow over the shallow banks and ungauged channels surrounding Rabbit Key Basin (Q_b) from the changes in basin volume anomaly ($\partial V_{RB}/\partial t = Q_T$) and measured channel flows (Q_c) as: $Q_b = Q_T - Q_c$ over 80 d during the wet and dry seasons (Figs. 9, 10). During both seasons there were persistent outflows through the channels that were nearly balanced by net inflows over the surrounding banks. Subtidal fluctuations of channel flow ranging from 25 to 150 m^3 s^{-1} appear to be correlated with similar variations in the

Table 3. Seasonal and annual mean flows (m^3 s^{-1}) through measured channels in Ninemile Bank, Twin Key Bank, and Sid transect across the northern part of Twin Key Basin. See Figure 2 for site locations.

Transport	Wet season	Dry season	Annual mean
Sid	98.0	11.9	56.0
Twin Key Bank	−15.5	−14.3	−14.9
Ninemile Bank	−44.4	−12.6	−28.5

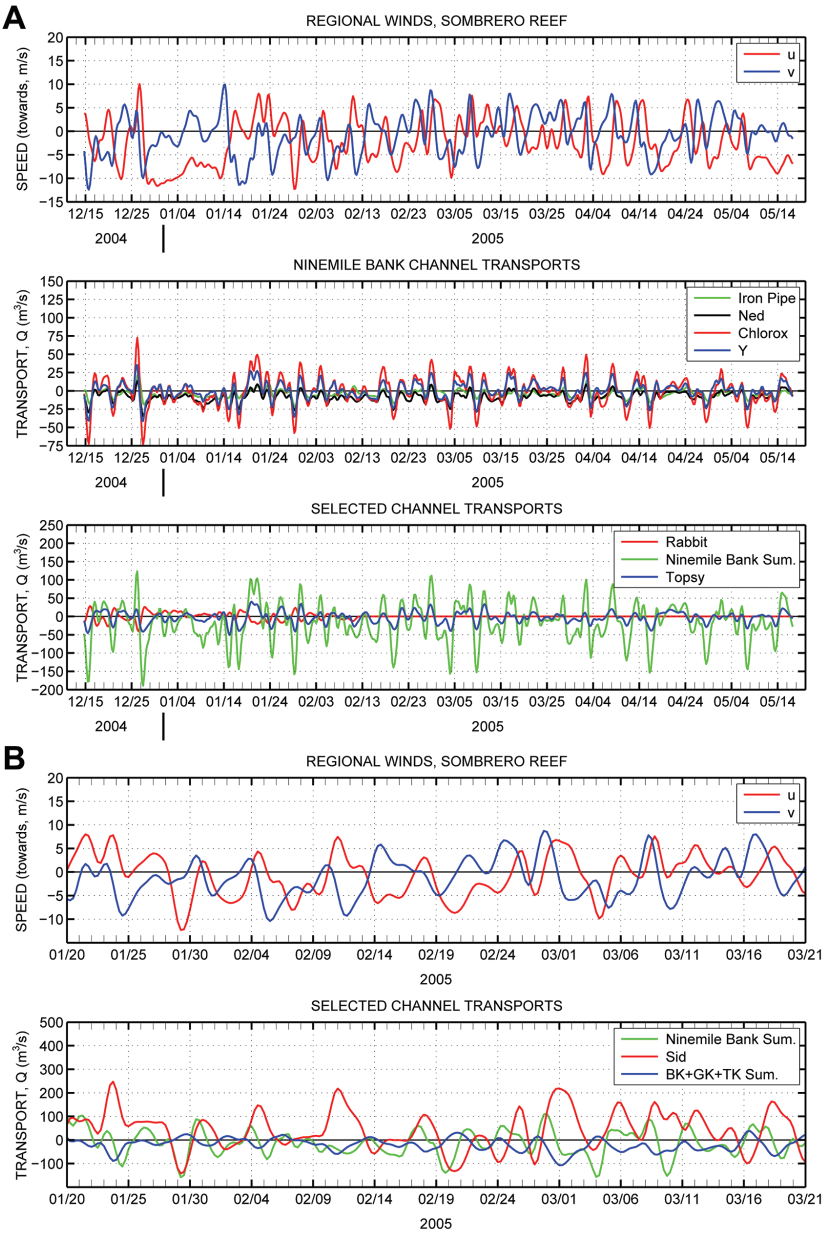

Figure 8. (A) Subtidal [40 Hour Low-Pass (HLP)] time series of east–west (U) and north–south (V) wind components from Sombrero Reef CMAN station (top panel), together with volume transports derived for the major flow channels to Rabbit Key Basin through Ninemile Bank for the dry season 2005 (middle panel). Positive values are inflows to the basin and negative are outflows. Bottom panel shows the sum of flow through Ninemile Bank Channels plus flows through Rabbit Key Channel at the east side of Rabbit Key Basin and Topsy Channel located at the southern end of Whipray Basin where negative transport represents flow out of Whipray Basin and toward Rabbit Key Basin. (B) U and V winds for the dry season (2005, top panel) with blow-up of the sum of western basin transports (40 HLP) through Ninemile Bank, Sid section across northern Twin Key Basin, and Twin Key Bank (sum of flow through Barnes Key Channel, Gopher Key Channel and Twin Key Channel: BK+GK+TK) (bottom panel). Positive transports represents inflows for both Rabbit Key and Twin Key Basins.

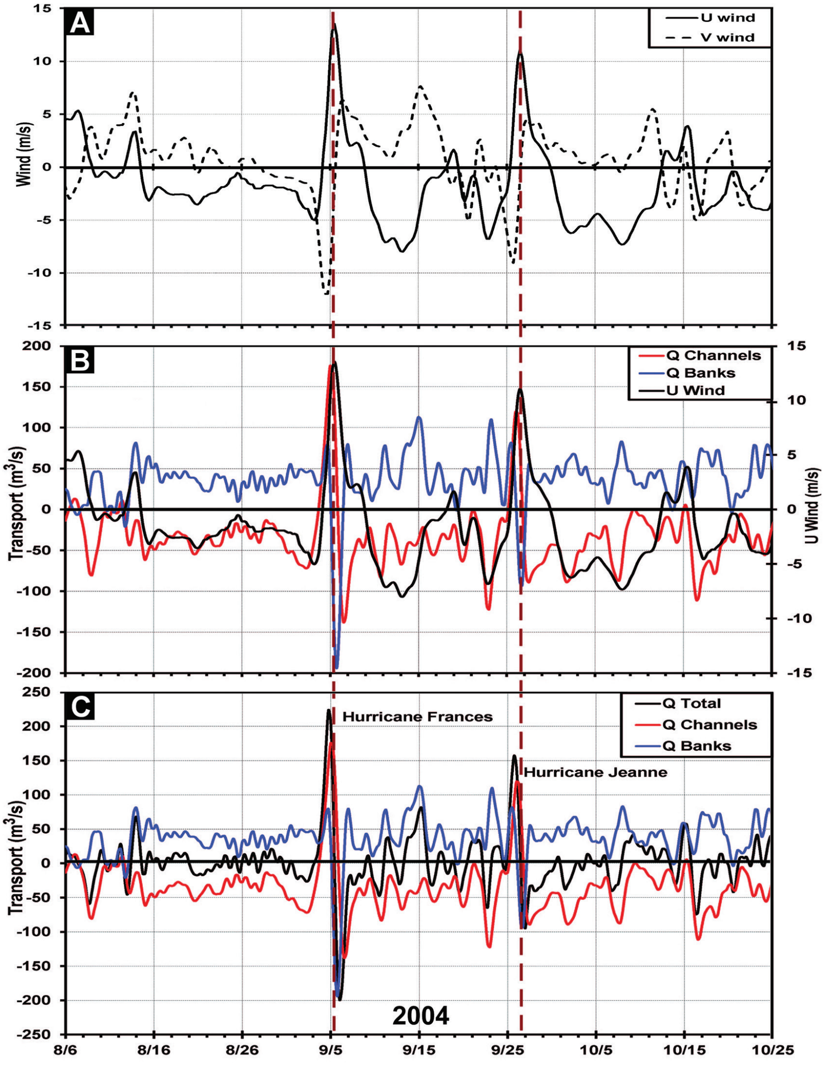

Figure 9. Subtidal flows to Rabbit Key Basin for an 80-d period during the wet season of 2004. Top panel displays wind components at Sombrero Lighthouse, middle panel plots channel flow (*Q* Channels) and bank flow (*Q* Banks) together with the east–west wind component, and the bottom panel plots time series of total flow (*Q* Total), channel flow (*Q* Channels) and bank flow (*Q* Banks). Positive transport represents inflow to the basin and negative values represent basin outflows.

total basin flow and closely balanced by opposing net inflows over the banks. Largest net basin transport variations occurred during hurricanes Frances and Jeanne. During the passage of Hurricane Frances the total basin transport changed from 200 $m^3 s^{-1}$ inflow to −200 $m^3 s^{-1}$ outflow over one day (Fig. 9). Hurricane Jeanne produced a change in total basin transport from 150 $m^3 s^{-1}$ inflow to −100 $m^3 s^{-1}$ outflow over one day. Net inflows to Rabbit Key Basin through the measured channels were mainly restricted to the dry season, when cold front passages caused zonal wind reversals toward the east with increased speeds. The influence of zonal winds on basin water exchange is clearly shown in Figures 9 and 10 by the significant visual correlation between channel transport and the east-west wind component. This correlation

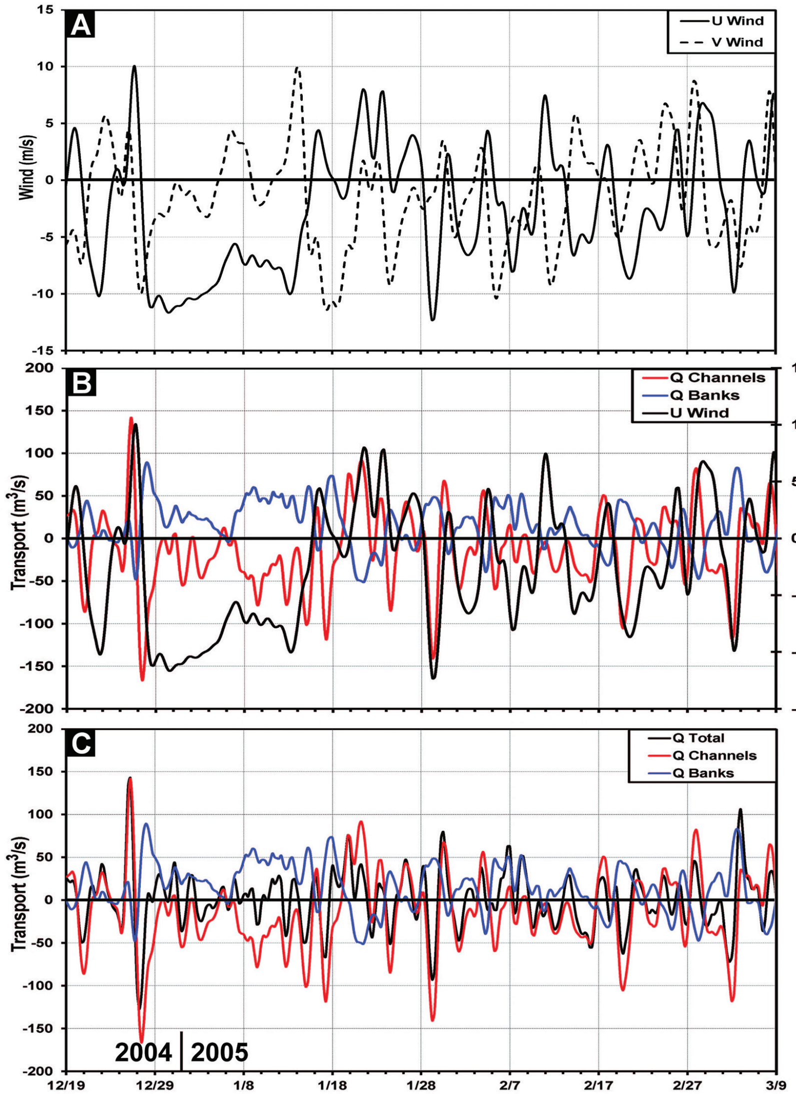

Figure 10. Subtidal flows to Rabbit Key Basin for an 80-d period during the dry season of 2005. Top panel displays wind components at Sombrero Lighthouse, middle panel plots channel flow (*Q* Channels) and bank flow (*Q* Banks) together with the east-west wind component, and the bottom panel plots time series of total flow (*Q* Total), channel flow (*Q* Channels) and bank flow (*Q* Banks). Positive transport values represent inflow to the basin and negative values represent basin outflows.

is strongest during the wet season when westward winds were more persistent (R^2 = 0.23). Meridional winds during cold front passages of the dry season tend to reduce the zonal wind influence on channel transports (R^2 = 0.11).

Seasonal and annual averages of flow balance for Rabbit Key Basin are given in Table 4. Seasonally-averaged channel transports show mean outflows of −57 $m^3 s^{-1}$ for the wet season and −13 $m^3 s^{-1}$ for the dry season that were nearly balanced by mean inflows over the surrounding banks. Standard deviations of channel and bank flows were of similar magnitude at ± 30 $m^3 s^{-1}$ for the wet season. However, dry season channel transport variations were somewhat larger at ± 41.9 $m^3 s^{-1}$ compared to

Table 4. Seasonal and annual means (SD) of total transport (Q_T) from Rabbit Key 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 2004 wet season and 2005 dry season. 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 Rabbit Basin are: mean depth, $h = 1.82$ m, surface area, $A = 40.97 \times 10^6$ m^2 = 40.97 km^2, mean volume, $V = 74.6 \times 10^6$ m^3.

Transport	Wet season	Dry season	Annual mean
Q_T	1.0 (33.2)	0.7 (29.6)	0.85
Q_c	−57.1 (31.9)	−13.1 (41.9)	−35.1 (36.9)
Q_b	58.0 (28.1)	13.8 (26.3)	35.9 (27.2)
Exchange time (mo)	0.5	2.1	0.8

± 26.3 $m^3 s^{-1}$ for the bank transport, which may be due to lower sea level in the dry season reducing flow over the shallower banks. The seasonal decrease in mean channel transport was caused by the greater occurrence of eastward winds in the dry season from cold front passages (Figs. 9, 10). Over the wet season, there was a net inflow of 58 $m^3 s^{-1}$ over the banks and small creeks surrounding Rabbit Key Basin, which when combined with the net outflow through the channels of −57 $m^3 s^{-1}$, results in a mean basin throughflow of about 57 $m^3 s^{-1}$. The mean depth of Rabbit Key Basin is 1.82 m and the surface area is estimated at 40.97×10^6 m^2, which gives a mean basin volume of 74.6×10^6 m^3. Therefore, if the mean volume remains constant, the net throughflow of 57 $m^3 s^{-1}$ would take approximately 2 wk to replace an equivalent basin water volume. The mean basin throughflow over the dry season is estimated at 13 $m^3 s^{-1}$, which would take 2.1 mo to replace the basin's mean water volume. The annual mean throughflow rate is estimated as the average of mean throughflows for the wet and dry seasons or 35 $m^3 s^{-1}$. At this flow rate it would take about 3 wk to replace the mean volume of Rabbit Basin.

Discussion

Salinity.—We have now completed a series of studies investigating the physical processes regulating water exchange between the interior basins of Florida Bay. Our methodology consisted of direct measurement over wet and dry seasons of basin salinity, sea level change, and volume flows between basins. Initially we focused on the north-central subregion of Whipray Basin (Fig. 1), characterized by prolonged periods of hypersalinity, which can lead to seagrass die-off and water quality degradation (Lee et al. 2006). High salinities have previously been attributed to evaporation of the shallow basin waters together with the lack of freshwater inputs. However, these factors alone would not lead to hypersalinity if it were not for the isolation of the basins. Adequate water exchange with surrounding basins would dilute the salt build-up and reduce hypersalinity development. In fact, we find that the very limited exchange of north-central basin waters with adjacent basins of Florida Bay results in long residence times, on the order of 6–12 mo (Lee et al. 2006, 2008). This suggests that there may be a simple solution to the hypersalinity condition that threatens the water quality of the region. During the dry season, a relatively small portion of the Everglades freshwater discharge to the northeast subregion of the bay could be diverted directly to McCormick Creek (Fig. 1), where it would continue to flow into Whipray Basin and aid in the dilution of salt build-up. At present, McCormick Creek discharges fresh water to Whipray Basin only during the wet season, at a mean rate of 3.5 $m^3 s^{-1}$. This inflow, together with seasonal rainfall, rapidly decreases salinity within the basin, thus ending hypersaline conditions and returning Whipray Basin to a healthy estuarine environment. The northeast subregion of Florida Bay receives fresh water at an annual mean rate of about 25 $m^3 s^{-1}$ through Taylor and Trout rivers and several other small rivers in the east. This rate of river inflow is sufficient to maintain salinity of the northeast basin waters below hypersaline conditions, as well as promote healthy seagrass beds and clear waters throughout the year (Lee et al. 2008). However, the northeast subregion is separated from Whipray Basin by the wide, shallow bank known as Crocodile Dragover (Fig. 1), which prevents any significant interaction between subregions.

The northeast subregion receives >90% of the Everglades fresh water delivered directly to Florida Bay. Most of this fresh water tends to be trapped within the subregion due to isolation by the surrounding banks and mangrove island chains. Similar to the north-central subregion, we find that basin water renewal is primarily controlled by local wind-driven circulation, resulting in weak water renewal rates and long residence times on the order of 1 yr (Lee et al. 2008). As a consequence of the isolation of the northeast subregion, the fresh water discharged from the Everglades becomes trapped there, consistently causing the bay's lowest mean salinity as well as the bay's largest annual change of salinity (Nuttle et al. 2000, Kelble et al. 2007). Surprisingly, the annual salinity variation of the isolated north-central subregion is of nearly equal magnitude to that of the northeast subregion, both responses apparently due to the basins' shallow depths and isolation. Kelble et al. (2007) found that there was a 1-mo lag in salinity of the north-central subregion in response to freshwater runoff compared to a 2-mo lag for the northeast subregion. The difference was attributed to the much shallower depths of the north-central subregion and an order of magnitude smaller mean volume, both of which enhance the basin's salinity response to freshwater discharge. This provides further evidence that a small diversion of river discharge from the northeast subregion to the north-central subregion would aid in the prevention of harmful hypersalinity conditions within Florida Bay.

We estimated the magnitude of fresh water needed to prevent hypersalinity development in the north-central region (see Appendix), and highly recommend that as part of the Everglades Restoration Project, a minimum of 3 $m^3 s^{-1}$ of freshwater discharge to Taylor River and Trout Creek be diverted to McCormick Creek during the dry season. River diversion is not necessary during the wet season as there is already ample flow through McCormick Creek at that time, and this coupled with increased precipitation would be sufficient to prevent hypersalinity development from occurring.

In the present study of the western basins of Florida Bay, we found an annual cycle of mean salinity with a range of 10, from a maximum of 45 in mid-July to a minimum of 35 in early October (Fig. 5). Surprisingly, a second salinity minimum occurred in the middle of the dry season when river discharge and precipitation were minimal (Figs. 3, 4, 5). Large-scale salinity surveys (Fig. 6) clearly indicate that this second salinity minimum in mid-winter was due to a low-salinity intrusion event coming from the southwest Florida shelf with salinities ranging from 35.0 to 35.5. The intrusion waters were part of a low-salinity coastal plume that extended southward along the west Florida coast from at least Charlotte Harbor (the northern extent of the survey) to the Florida Keys. The plume then entered the Atlantic coastal waters of the Florida Keys through Long Key Channel, Channels 5 and 2 (Fig. 1). The mean salinity of western bay waters continued to be diluted by the intrusion event over a 4-mo period from December 2004 through March 2005. Even the north-central subregion was freshened by this event, with salinities in Whipray Basin ranging from 42 to 45 in January, then dropping to below 40 for February and March before rising back to between 40 and 44 in April, and then near 50 in July. The low-salinity band did not appear to affect salinity within the southeast subregion of the bay, presumably because it is isolated from the southwest shelf flow by the shallow Peterson Key Bank and there is a vigorous tidal exchange with Atlantic coastal waters through Lignumvitae, Indian Key, and Teatable Key Channels.

River discharge plumes along coasts in the northern hemisphere are forced to turn toward the right due to the Coriolis influence (Csanady 1984, Kourafalou et al. 1996). However, in the Ten Thousand Islands coastal region, the mean flow is toward the south in response to a mean sea level slope toward the southeast, which is a result of the higher standing Loop Current in the Gulf of Mexico compared to the lower sea level of the Florida Current along the Florida Keys (Smith 1997, Lee and Smith 2002). Freshwater discharge from the small rivers and creeks of southwest Florida are entrained in this southward flow and transported through the passages between the Florida Keys. It is not uncommon for these west coast low-salinity plumes to transport harmful algal blooms, such as red tides (Hu et al. 2005), to western Florida Bay and the Florida Keys reef tract.

Wind-induced Water Renewal and Residence Times.—Previous observational and modeling studies of Florida Bay suggested that the residence times of interior basin waters increase with distance from the southwest Florida shelf due to frictional dampening of tides and currents by the quilt-like arrangement of shallow banks and interior basins (Wang et al. 1994, Boyer et al. 1997, Boyer et al. 1999, Nuttle et al. 2000, Lee et al. 2006, Kelble et al. 2007). We find that low-frequency wind events on 2-d to 2-wk time scales set up net flows that renew interior basin waters on time scales of 6–12 mo (Lee et al. 2006, 2008), consistent with renewal times estimated from historical and more recent salinity studies (Nuttle et al. 2000, Kelble et al. 2007).

Tidally-induced volume transports through the channels of Ninemile Bank are quite strong, ranging from 70 to near 290 $m^3 s^{-1}$ as shown by the 3 HLP transport statistics of Tables 1 and 2. Although these tidally-induced flows may have a significant influence on water properties within 1 or 2 tidal excursion lengths of Ninemile Bank, by far the more important basin flushing mechanism is wind-forced throughflow, which results in westward-directed net outflows through the measured channels balanced by net inflows over the surrounding shallow banks in response to prevailing westward winds over the Florida Keys. Westward throughflow events in Rabbit Basin are clearly evident in Figures 9 and 10 over both the wet and dry seasons, and are visually well correlated with westward wind events with few exceptions. The basin-wide response to the westward wind forcing sets up a net downwind flow over the shallow banks and unmeasured channels surrounding Rabbit Key Basin, causing a net inflow that is balanced by a net outflow through the instrumented channels of Ninemile and Rabbit Key Banks, as was explained previously in the Methods and shown in Figures 9 and 10. Eastward winds are typically associated with cold front passages during the dry season and have the opposite effect on basin net water exchange, causing net inflows through the measured channels balanced by net outflows over the shallow banks (Fig. 10).

During the wet season, westward winds can persist for periods of 10–20 d (Fig. 9), and are influential in causing the 2-wk time scale estimated for renewal of Rabbit Key Basin waters by the wind-forced throughflow (Table 4). Also, in the wet season, mean sea level in Florida Bay stands about 30 cm higher than during the dry season due to thermal expansion of seawater following summer heating. Higher mean sea levels will decrease friction on the shallow banks and lead to larger bank overflows. During the dry season, mean sea level is lower and the seasonally-averaged throughflow decreases to approximately 13.5 $m^3 s^{-1}$, with standard deviations of channel flows (± 42 $m^3 s^{-1}$) being about 10 $m^3 s^{-1}$ larger than during the wet season and fluctuations of bank flows remaining nearly the same as during the wet season (Table 4). Also there was a 20-d period from late December to mid January of strong westward wind that generated a persistent westward throughflow in Rabbit Key Basin (Fig. 10) that averaged about 50 $m^3 s^{-1}$ and could replace the basin's mean volume in 18 d. Wind forcing for the remainder of the dry season was dominated by the passage of cold fronts on time scales of 4–8 d.

Rabbit Key Basin outflows mix with either the southwest shelf waters or Twin Key Basin waters depending on the direction of the outflow. The net volume of water entering Rabbit Key Basin will consist of some fraction of "new waters" that had not previously been inside the basin. The mean amplitude of inflow events from either channel or bank transports is approximately 34 $m^3 s^{-1}$. If we conservatively estimate that 50% of these net inflows represents new water, then the effective basin flushing rate becomes 17 $m^3 s^{-1}$, and the renewal time of the basin mean volume becomes approximately 1.7 mo, which is similar to the dry season exchange time (Table 4). This flushing rate is believed to be somewhat conservative since there is considerable coastal flow along the seaward edge of Ninemile Bank, which would rapidly remove outflowing basin waters and increase the percentage of new water with inflows from the west.

Mean Circulation of Florida Bay.—We have completed observational studies of circulation and exchange processes within the north-central, northeast, and western subregions of Florida Bay. For each region, measurements of volume transports through channels connecting interior basins have been used, together with time series of basin total volume transport derived from sea level measurements, to estimate basin flushing rates and residence times, and to identify the important physical processes regulating basin water renewal. In the north-central and northeast basins, wind-forced throughflows were found to be weak and require on the order of 1 yr to replace an equivalent mean volume of the basins. However, in the western subregion of Rabbit and Twin Key Basins, wind-forced throughflows together with enhanced tidal exchange due to the closer proximity to the ocean were found to have a more significant effect on basin water renewal, causing moderation of seasonal changes in salinity and a decreased residence time of about 1 mo.

Florida Bay mean flow pathways were estimated from annual mean volume transport measurements, river discharges, and derived bank flow estimates, and are shown in Figure 11. The annual river discharge to the bay of 27 $m^3 s^{-1}$ is essentially trapped in the northeastern subregion and does little to dilute the hypersalinity of the north-central bay. There is a weak mean flow pathway from Flamingo Channel (refer to Fig.

1 for names of channels and banks) eastward across the northern banks of the Tin Can Channel area and then southward through the north-central basin of 4 $m^3 s^{-1}$. There is also a much stronger clockwise mean flow pattern extending from the major branch of Flamingo Channel through Conchie Channel and around the north side of Dildo Key Bank, then southward through the Sid section of Twin Key Basin. The annual average magnitude of this clockwise inflow was measured at the Sid section at 55 $m^3 s^{-1}$. Mean outflows measured through Ninemile Bank and Twin Key Bank indicate that the large inflow from Flamingo tends to split, with approximately 35 $m^3 s^{-1}$ exiting through Rabbit Key Basin and onto the southwest shelf through Ninemile Bank, while the remaining 20 $m^3 s^{-1}$ continues south through Twin Key Basin and exits to the southeast subregion of Florida Bay through Twin Key Bank. This clockwise circulation through the western basins of Florida Bay generally takes place on time scales <1 yr. Eventually these waters will rejoin the 800 $m^3 s^{-1}$ net southward coastal flow on the southwest Florida shelf (Lee and Smith 2002) that provides the connection for transport of river discharges from the southwest Florida shelf and Ten Thousand Islands area (Shark, Harney, Lostmans, and Broad Rivers) to the western basins of Florida Bay and ultimately the Florida Keys Atlantic reef tract.

Conclusions

Completing our studies of circulation and exchange processes within the interior basins of Florida Bay, we find a common mechanism controlling basin water renewal for the three subregions studied: the north-central region of hypersalinity and 1-yr residence time; the northeast subregion of low salinity from direct river discharge and a similar 1-yr residence time; and the western subregion which undergoes direct exchange with southwest shelf waters and has a much shorter residence time of approximately 1 mo. In each of these subregions, we observe that local winds, coherent over spatial scales larger than Florida Bay, produce a similar bank-basin flow response with net downwind flows through measured channels balanced by net inflows over the surrounding shallow banks and small, unmeasured channels.

This response results in a net basin throughflow that regulates basin water renewal rates. The flushing rates of the western basins appear to be sufficient to maintain healthy coastal marine environments with clear waters and robust seagrass beds, and little development of hypersalinity. In addition, there is a strong southward-directed coastal flow along the western boundary of Florida Bay that transports west Florida shelf waters through the Florida Keys channels to the Florida Keys Atlantic coastal waters (Fig. 11). This coastal flow serves to rapidly remove western basin discharges so that only a small fraction of discharge water reenters the basin, thus increasing flushing rates. Finally, we have discovered a strong clockwise circulation pattern through the western subregion of Florida Bay that helps to maintain healthy water quality and provides pathways for larval recruitment. This western basin circulation pattern appears to be fed by a branch of the southwest shelf coastal flow that enters Flamingo Channel and Conchie Channel and is forced to turn southward through Twin Key Basin by the shallow banks surrounding the north-central subregion, whereupon the flow splits with part exiting Florida Bay through Rabbit Basin and Ninemile Bank and the remainder flowing through Twin Key Bank and into the southeast subregion of the bay and direct exchange with Atlantic coastal waters of the Florida Keys (Fig. 11).

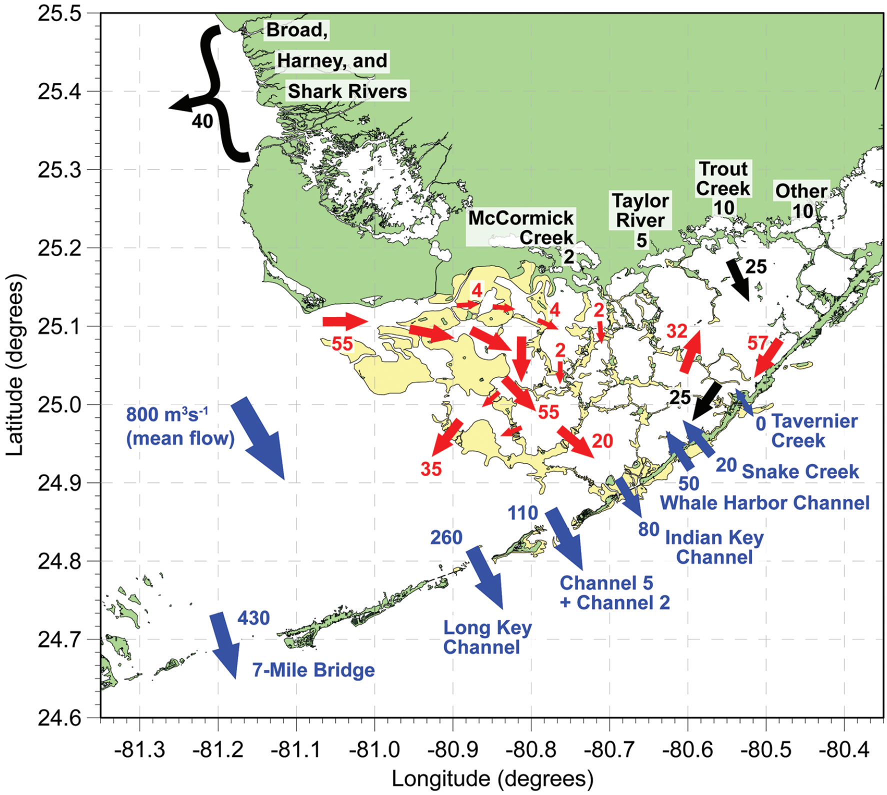

Figure 11. Annual mean volume transports ($m^3\ s^{-1}$) for measured channels in Florida Bay (red arrows and numbers) and through the tidal passes between the Florida Keys (blue arrows and numbers). The mean southward flow through the southwest shelf and Florida Keys tidal channels is also given. Mean river discharge is shown with black arrows and numbers.

We would be remiss if we did not conclude this work with the important observation and recommendation made in our previous studies of the north-central and northeast subregions (Lee et al. 2006, 2008) and now quantified in the present study. A straightforward solution to water quality degradation from hypersalinity development and sea grass die-off in Florida Bay is possible through the diversion of 3 $m^3\ s^{-1}$ of freshwater discharge from Taylor and Trout rivers to McCormick Creek during the dry season so the water would flow directly into the north-central subregion, the focal point of hypersalinity development in Florida Bay.

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Literature Cited

Boyer JN, Fourqurean JW, Jones RD. 1997. Spatial characterization of water quality in Florida Bay and Whitewater Bay by multivariate analyses: Zones of similar influence. Estuaries. 20:743–758. http://dx.doi.org/10.2307/1352248

Boyer JN, Fourqurean JW, Jones RD. 1999. Seasonal and long-term trends in the water quality of Florida Bay. Estuaries. 22:417–430. http://dx.doi.org/10.2307/1353208

Csanady GT. 1984. Circulation induced by river inflow in well mixed water over a sloping continental shelf. J Phys Oceanogr. 14:1703–1711. http://dx.doi.org/10.1175/1520-0485(1984)014<1703:CIBRII>2.0.CO;2

Eisensmith S. 1985. PlotIt interactive Graphics and Statistics, Version 1.0, Scientific Programming Enterprises, Haslett, Minnesota.

Florida Forever Act (FFA). 2000. Florida Statutes Chapter 259.105.

Fourqurean JW, Robblee MB. 1999. Florida Bay: a history of recent ecological changes. Estuaries. 22:345–357. http://dx.doi.org/10.2307/1353203

Hittle CD, Zucker MA. 2004. Northeastern Florida Bay estuarine creek data, water years 1996–2000. US Geological Survey Data Series report 105. Miami, Florida.

Hu C, Muller-Karger FE, Taylor C, Carder KL, Kelble C, Johns E, Heil CA. 2005. Red tide detection and tracing using MODIS fluorescence data: a regional example in SW Florida coastal waters. Remote Sens Environ. 97:311–321. http://dx.doi.org/10.1016/j.rse.2005.05.013

Johns E, Lee TN. 2012. Weather and climate strongly influence salinity, water quality, and circulation of south Florida coastal waters and bays. *In:* Kruczynski WL, Fletcher PJ, editors. Tropical connections: south Florida's marine environment. IAN Press, University of Maryland Center for Environmental Science, Cambridge, Maryland. p. 72–72.

Kelble CR, Johns EM, Nuttle WK, Lee TN, Smith RH, Ortner PB. 2007. Salinity Patterns of Florida Bay. Estuar Coast Shelf Sci. 71:318–334. http://dx.doi.org/10.1016/j.ecss.2006.08.006

Kourafalou VH, Oey L, Wang J, Lee TN. 1996. The fate of river discharge on the continental shelf 1. Modeling the river plume and the inner shelf coastal current. J Geophys Res. 101:3415–3434. http://dx.doi.org/10.1029/95JC03024

Lee TN, Williams E. 1999. Mean distribution and seasonal variability of coastal currents and temperature in the Florida Keys with implications for larval recruitment. Bull Mar Sci. 64:35–56.

Lee TN, Smith NP. 2002. Volume transport variability through the Florida Keys tidal channels. J Cont Shelf Res. 22:1361–1377. http://dx.doi.org/10.1016/S0278-4343(02)00003-1

Lee TN, Johns E, Melo N, Smith RH, Ortner P, Smith D. 2006. On Florida Bay hypersalinity and water exchange. Bull Mar Sci. 79:301–327.

Lee TN, Melo N, Johns E, Kelble C, Smith RH, Ortner P. 2008. On water renewal and salinity variability in the northeast subregion of Florida Bay. Bull Mar Sci. 82:83–105.

Nuttle WK, Fourqurean J, Cosby B, Zieman JC, Robblee MB. 2000. The influence of net freshwater supply on salinity in Florida Bay. Water Resour Res. 36:1805–1822. http://dx.doi.org/10.1029/1999WR900352

Press WH, Teucholsky SA, Vetterling WT, Flannery BP. 1992. Numerical recipes in fortran: the art of scientific computing, 2nd ed. Cambridge: Cambridge University Press.

Safak I, Wiberg PL, Richardson DL, Kurun MO. 2015. Controls on residence times and exchange in a system of shallow coastal bays. J Cont Shelf Res. 97:7–20. http://dx.doi.org/10.1016/j.csr.2015.01.009

Smith NP. 1997. An Introduction to the Tides of Florida Bay. Fla Sci. 60:53–67.

Umgiesser G, Ferrarin C, Cucco A, De Pascalis F, Bellafiore D, Ghezzo M, Bajo M. 2014. Comparative hydrodynamics of 10 Mediterranean lagoons by means of numerical modeling. J. Geophys. Res. Oceans. 119:2212–2226. http://dx.doi.org/10.1002/2013JC009512

Wang J, van de Kreeke J, Krishnan N, Smith D. 1994. Wind and tide response in Florida Bay. Bull Mar Sci. 54:579–601.

Water Resources Development Act (WRDA). 2000. Public Law 106-514 Title VI, section 601.

Appendix

To estimate the magnitude of fresh water needed to prevent hypersalinity development in the north-central subregion, we use a simple salt balance approach for Whipray Basin, the focus area of hypersalinity development conservation of volume flow for Whipray Basin is written as:

$$Qi + r + P = Qo + E \quad \text{(Eq. 2)}$$

where Qi = mean inflow to the basin over the dry season; Qo = basin mean outflow; r = mean river inflow; P = mean precipitation; and E = mean evaporation rate. Conservation of salt is written as:

$$So\ Qo = Si\ Qi \quad \text{(Eq. 3)}$$

with So and Si equaling the mean salinity of Whipray outflow and inflow waters. Rearranging Equation 2 and Equation 3 above and solving for the salinity of the outflow waters gives:

$$So = Si\ Qi/Qo = Si\ Qi/(Qi + r + P - E) \quad \text{(Eq. 4)}$$

Using the values for the above terms given in tables 4, 5, and 6 from Lee et al. (2006) for Whipray Basin during the dry season of 2001 we have: Si = 42; Qi = 11.2 $m^3\ s^{-1}$; P = 3.07 $m^3\ s^{-1}$; and E = −4.25 $m^3\ s^{-1}$. Using r = 3 $m^3\ s^{-1}$ for river inflow through McCormick Creek during the dry season instead of zero gives the mean salinity of Whipray Basin outflow waters as: So = 36.13. Thus it only requires a small flow of fresh water through McCormick Creek to prevent hypersalinity from developing in Whipray Basin during the dry season. Controlling hypersalinity at the focal point of its development in Florida Bay would greatly reduce the possibility of large-scale development of hypersalinity and accompanying seagrass die-off.

Therefore it is highly recommended that as part of the Everglades Restoration Project, a minimum of 3 $m^3\ s^{-1}$ of freshwater discharge to Taylor River and Trout Creek be diverted to McCormick Creek during the dry season.