ON FLORIDA BAY HYPERSALINITY AND WATER EXCHANGE

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ABSTRACT

Florida Bay is made up of a collection of shallow basins separated by mud banks and mangrove islands situated between the Florida mainland and the Florida Keys. The bay is located downstream of the Everglades discharge that has been altered over the past century due to South Florida land use practices, leading to reduced water delivery to Florida Bay and elevated salinities. The reduced freshwater flow has had the strongest impacts in the north-central region of the bay, in the vicinity of Whipray basin (WB), where extreme hypersalinity can develop along with degradation of water quality and seagrass die-off. We use direct measurement of water exchange between Whipray and surrounding regions for dry and wet seasons of 2001 together with detailed salinity surveys, sea level measurements, and freshwater flux estimates to evaluate water and salt balances, and to estimate basin water renewal rates and residence times. Water renewal of WB is strongly regulated by local wind forcing. Winds toward the east from the passage of cold fronts during the winter/spring dry season resulted in a mean eastward flow through Whipray of 11 $m^3 s^{-1}$, with inflows over the wide western mud banks, and outflows through the eastern and southern channels. Conversely, winds toward the southwest and west typical of the summer/fall wet season produced a mean throughflow of 3 $m^3 s^{-1}$, with inflows through the eastern channels and outflows over the western banks. The time required for complete renewal of WB waters is estimated at 6–12 mo. Water balances are used to estimate a weak seasonal average groundwater input to Whipray of 1.7 $m^3 s^{-1}$ during the dry season and a negative groundwater flow or downwelling of -4.7 $m^3 s^{-1}$ for the wet season. Hypersalinity development was found to be caused by the combination of reduced freshwater inputs during the dry season combined with weak basin water renewal rates. Hypersalinity development could be greatly reduced by diversion of freshwater to WB via McCormick Creek during dry seasons.

Hypersaline conditions (salinity > 40) develop in the north-central region of Florida Bay as part of the seasonal cycle of freshwater fluxes. Concerns have been raised that prolonged or extreme development of hypersalinity may make the ecosystem more vulnerable to seagrass die-off and contribute to the development of blue-green algal blooms that could have larger impacts on marine ecosystems of Florida Bay, the southwest Florida shelf, and the coral reefs of the Florida Keys National Marine Sanctuary. As part of the Comprehensive Everglades Restoration Plan (CERP; WRDA, 2000 and FFA, 2000), efforts are underway to restore the spatial and temporal delivery of freshwater to Florida Bay to the more natural flow conditions which occurred prior to the construction of dikes and canals that diverted freshwater from the Everglades as part of previous water management practices (Light and Dineen, 1994). Comprehensive modeling efforts have begun to evaluate the fate of different freshwater discharge scenarios (Hamrick and Moustafa, 2003). However, until recently no direct measurements of water exchange between the interior basins of Florida Bay were available to quantify basin renewal times and verify models. Previous residence time estimates were based on long-term salinity data sets using water volume and salt budget methods (Nuttle et al., 2000). Our purpose is to present the results of new direct observations of water exchange between Whipray basin (WB) and adjacent basins in the central region of Florida Bay, from which we estimate basin residence time, water and salt budgets, and describe the controlling role of local wind forcing on bay circulation and exchange.

Florida Bay Physical Processes.—Florida Bay is located at the southern end of Everglades National Park (ENP), between the Florida Keys and the mainland. The bay is made up of a complex network of shallow basins with depths ranging from 1 to 3 m, separated by shallow mud banks and mangrove islands (Fig. 1). Connection between basins occurs through narrow channels and over the shallow banks. The mud banks are largely covered by seagrass that can reach to the water surface. Water depths over the banks are typically < 0.3 m. During periods of low sea level (e.g., winter dry season or strong winds toward the southwest), the banks can become exposed, causing further isolation of the interior basins. Although the bay is openly connected to the southwest Florida shelf along its wide western boundary, exchange with the Atlantic coastal zone of the Keys is restricted to a few narrow tidal channels between the Keys island chain. The northern boundary of the bay is fringed with mangroves, and freshwater input is presently confined to the northeastern region through Taylor Slough and Trout Creek. The combined tidal harmonics of the Gulf of Mexico and the Atlantic produce a mixed tide along the western boundary of the bay with a 1–1.5 m tidal range. Surprisingly, the largest tide on the U. S. eastern coast south of Brunswick, Georgia, occurs nearby at the mouth of Shark River, where the tidal range can exceed 2 m during spring tides.

Within Florida Bay, rapid fall-off of tidal range with distance from the western boundary (Wang et al., 1994) and dramatic increases in observed interior salinities (Fourqurean et al., 1993; Nuttle et al., 2000) indicate poor exchange of the northeast and central portions of the bay with adjacent subregions. Nuttle et al. (2000) estimated the seasonal cycle of freshwater fluxes to Florida Bay for the period 1970–1995. There are essentially two seasons defined by monthly average rainfall: the winter/spring dry season and the summer/fall wet season. Rainfall and evaporation water flux for the bay as a whole was found to have large seasonal changes that tend to nearly balance annually. Freshwater discharge is geographically restricted to the northeast region of the bay except for periods of very high sea level and rainfall. Although river discharge represents only about 10% of the total annual freshwater supply to the bay, it has a controlling influence on salinity variability in the northeast region. Nuttle et al. (2000) also combined the available salinity data for the 31 yr period 1965–1995 to estimate mean seasonal cycles of salinity for the east, west, south, and central regions of the bay. All regions show a maximum monthly mean salinity at the end of the dry season and a minimum toward the end of the wet season. Largest amplitudes of seasonal cycles were found in the central and eastern regions, suggesting greater isolation from the moderating effects of southwest Florida shelf waters, as compared to the western and southern regions where greater exchange with the adjacent shelf waters is to be expected. Maximum salinities occurred in the central region, indicating not only a greater degree of isolation, but also, the absence of direct riverine inputs. Minimum salinities were found in the northeast region, where most of the river discharge occurs.

Long-term salinity measurements from Florida Bay reveal considerable interannual variability of bay salinities, reversal of the seasonal salinity cycle during El Niño events, and decade-long trends of increasing/decreasing salinity during drought/wet

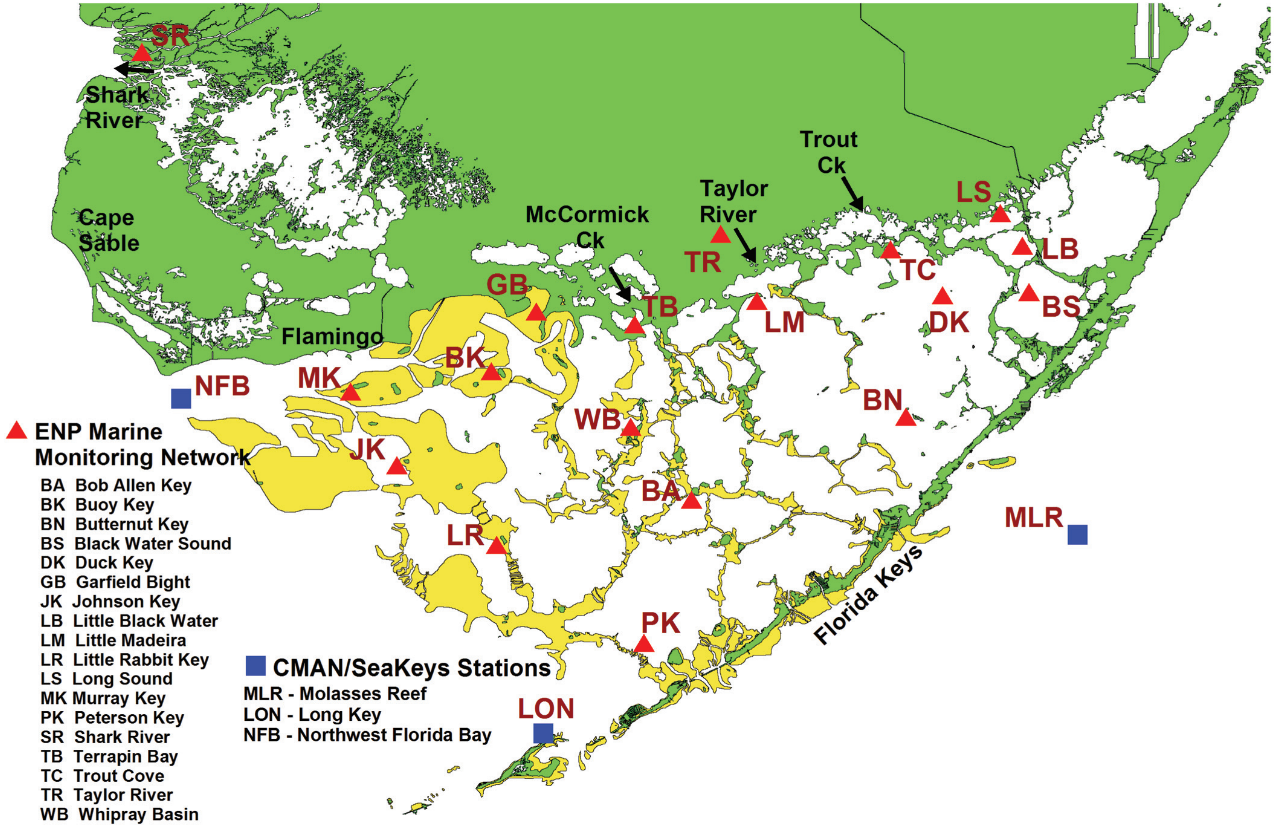

Figure 1. Location of Everglades National Park marine monitoring stations in Florida Bay (triangles), CMAN/SeaKeys wind stations (squares), and the location of freshwater discharge points (arrows) superimposed on Florida Bay bank/basin configuration (yellow/white) and mangrove islands (green).

periods (Orlando et al., 1998; Boyer et al., 1999; Nuttle et al., 2000; Johns et al., 2001). During prolonged or multiple dry seasons hypersalinity conditions in the central bay can exceed 70 (Fourqurean and Robblee, 1999; Swart et al., 1999). Hypersalinity development in Florida Bay has been associated with seagrass die-off, increased chlorophyll and turbidity levels, and loss of nursery function for important commercial species, such as pink shrimp (Zieman et al., 1988; Robblee et al., 1991; Nance, 1994; Fourqurean and Robblee, 1999; Boyer et al., 1999). Recent measurements indicate a drought occurred during 1989 and 1990, followed by a wet period through 1997. A strong El Niño event occurred between 1998 and 1999 that ended with a wet fall in 1999 due to the passage of several tropical storms. The years 2000 and 2001 represent another drought period followed by a new freshening with increased numbers of tropical storms from 2002 to the present (C. Kelble, NOAA/AOML, unpubl. data). Monitoring data suggest that not only do bay-wide salinities decrease during wet periods, but there is also a general trend for decreased turbidity and chlorophyll levels, all of which indicate improved water quality and ecosystem health (Boyer et al., 1999).

Methods

Our observational program (Fig. 2) was focused on determining water and salt flux between WB and the adjacent regions of Florida Bay from direct measurements of current velocity, salinity, temperature, and sea level with the goal of estimating residence times and improving our understanding of the physical processes involved. WB was chosen for this central basin study, as it is highly isolated by surrounding mud banks and mangrove islands, receives little river discharge except during intense wet periods, and develops extreme hypersalinity during droughts (Fourqurean et al., 1993; Nuttle et al., 2000; Johns et al., 2001; C. Kelble, NOAA/AOML, unpubl. data).

Currents, salinity, and temperature were measured in the flow channels connecting WB with the surrounding basins during dry (Mar 28–Jul 19) and wet (Sep 3–Nov 19) seasons of 2001 (Fig. 2). 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. WB is extremely shallow with a mean depth of only 0.65 m, requiring considerable care to locate channels with the minimum depth of 1.5 m that is needed for the proper placement of the current meters. Each current meter was also equipped with a SeaBird SBE 37 MicroCat conductivity and temperature recorder set to a 30 min sampling interval. All time series data were smoothed slightly with a 3 hour low-pass (HLP) filter and subsampled at hourly intervals. Due to mechanical problems at Crocodile there was a loss of 1.5 mo of data at the end of the record during the dry season and 1.3 mo at the start of the wet season. There was also a 2 wk data gap in the middle of the Twisty record of the wet season, so the statistics (Table 1) are given for both parts of the record before and after this gap. Current time series were converted to along-channel volume transport time series for the Twisty and Topsy locations (Fig. 2) using linear correlations of currents with shipboard measured volume transports across the channel transect. 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 average transports were made from 4 to 6 ADCP transects per ensemble. Each transect took about 4 min at Topsy and 12 min at Twisty, resulting in ensemble averaged transports over 16–24 min periods at Topsy, and 48–72 min periods at Twisty. Data recovery of ADCP velocity profiles typically ranged from 80% to 100% for water depths > 1.2 m and boat speeds < 2.5 m^{-1}. At Crocodile and Dump locations (Fig. 2) the shipboard ADCP technique could not be

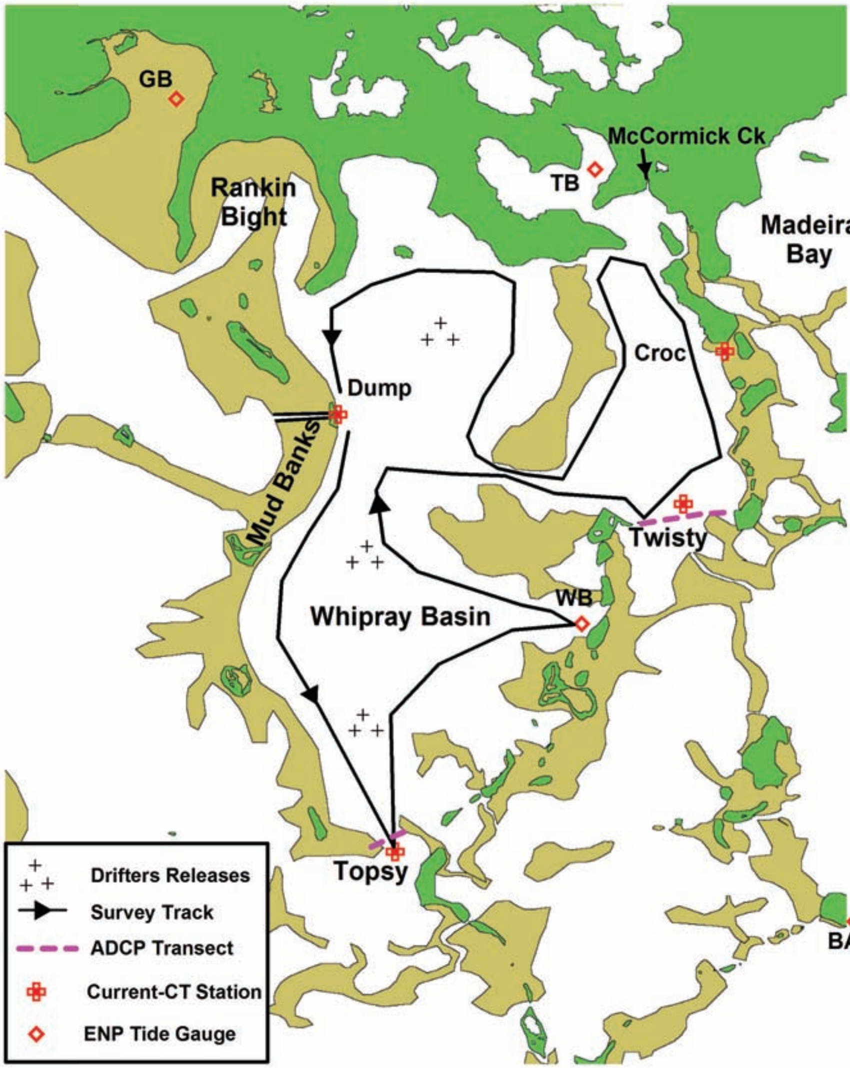

Figure 2. Location of Whipray Basin measurement stations: crosses indicate current, temperature, and salinity stations; diamonds show Everglades National Park tide stations; groups of 3 small crosses show drifter release sites; ADCP transport transects are shown with dashed lines and vessel survey track with solid bold line, upon which the arrow heads indicate vessel heading.

used due to the shallow water depths and narrow channel widths. Therefore, transport time series were derived at these locations by multiplying the cross-sectional area times the measured along-channel currents. Cross-sectional area at Crocodile was 23.7 m^2, where the width and mean depth were 23.7 and 1.0 m, respectively. At Dump the cross-sectional area was 22.8 m^2, and the width and mean depth were 22.8 and 1.0 m. Sea level measurements were not available at these two channels, so sea level was assumed to be constant. Standard deviations of sea level measurements taken by the ENP array within WB during our study period were approximately ± 0.1 m, which indicates that neglecting sea level variations in the transport derivations could introduce an error of approximately 10%. For the Crocodile and Dump sections where transports range from ± 10 $m^3 s^{-1}$, this error was estimated at ± 1 $m^3 s^{-1}$ and is not

Table 1. First order statistics of 3-hr low-pass (HLP) filtered along-channel currents (cm s^{-1}) from channels to Whipray Basin and northwest Florida Bay wind components (m s^{-1}) over record lengths during 2001 dry and wet seasons. Positive currents represent inflows to WB and negative values define outflows.

	Start m/d/h	End m/d/h	Data Pts	Mean	± SD	Max	Min	Range	Variance
Dry season									
Wind U	3/26/0000	7/20/0000	2,785	−2.6	3.9	9.9	−13.1	23.9	15.1
Wind V	3/26/0000	7/20/0000	2,785	0.1	3.2	11.5	−11.0	22.5	10.4
Crocodile	3/27/1705	6/04/1005	9,895	8.3	21.3	58.9	−37.8	96.7	452.9
Twisty	3/27/1705	7/19/0635	16,354	−0.1	2.8	8.9	−10.4	19.4	7.6
Topsy	3/27/1705	7/19/0635	16,354	−0.5	5.7	16.2	−18.4	34.6	32.3
Dump	3/27/1705	7/19/0635	16,354	0.8	18.8	67.7	−54.7	122.4	355.3
Wet season									
Wind U	9/3/1500	11/19/1200	1,846	−2.7	3.6	12.1	−14.4	26.5	13.1
Wind V	9/3/1500	11/19/1200	1,846	−1.5	3.6	14.2	−12.0	26.2	13.0
Crocodile	10/11/1855	11/16/1825	10,363	5.2	16.9	67.5	−29.7	97.2	286.2
Twisty a	9/3/1800	9/30/0000	7,561	−1.0	3.8	20.9	−19.1	40.0	14.4
Twisty b	10/15/0000	11/19/1200	10,225	2.0	4.2	14.9	−9.8	24.8	17.6
Topsy	9/3/1500	11/17/2110	21,675	−1.0	5.8	27.1	−31.5	58.5	33.1
Dump	9/3/1500	11/17/2110	21,675	−2.8	21.5	111.0	−92.1	203.1	462.9

considered significant. The missing transport time series at Crocodile (from gaps in current measurement) was filled using a linear regression with the highly coherent Dump transports, which accounted for about 80% of the Crocodile transport variability during the dry season and 90% during the wet season. A similar approach was used to replace the missing 2 wk period of transports at Twisty during the wet season with a regression on the east-west wind, which accounted for 70% of Twisty's transport variance. These reconstructed transport time series provide an expanded data set of equal length that is more representative of seasonal time durations.

Synoptic spatial surveys of WB salinity patterns were made throughout the dry and wet 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 ms^{-1}, which resulted in a spatial resolution of measured parameters of about 70 m. It generally took < 2 hrs to complete a detailed survey (see Fig. 2) of the entire basin and adjacent regions. Synoptic salinity surveys of the entire Florida Bay were conducted monthly from the R/V Virginia K using the same recording thermosalinograph (Johns et al., 2001 and C. Kelble, NOAA/AOML, unpubl. data). Each survey was completed in 2 d, 1 d for the outer portion of the bay and 1 d for the inner area. Tidal excursion lengths are quite small in the interior of the bay and spatial salinity patterns were found to have little variation on daily time scales. Vertical CTD profiles were collected at a network of 40 stations within basin interiors, together with a suite of water quality parameters. Salinity contouring from gridded fields, as well as basin average salinity, were determined using Golden Software's "Surfer" routine. Surface current trajectory patterns were observed several times during each season using specially designed shallow water drifters consisting of small discs that floated at the surface with drogued skirts that extend 0.5 m below the discs. GPS positions were recorded internally and transmitted to ARGOS satellite. Comparison of these shallow drifters with dye patch movements revealed good agreement in drift direction with a small speed error caused by wind slippage (Melo et al., 2003). Sea level variability for WB and the Florida Bay as a whole was determined from the ENP monitoring network (Fig. 1; D. Smith, 1999). Local wind time series were obtained from CMAN and SeaKeys monitoring stations in the Florida Keys and northwest Florida Bay as part of a cooperative agreement between Florida Institute of Oceanography (FIO) and

NOAA/NDBC through the SEAKEYS Program. Synoptic winds are highly coherent over the study area (Lee and Williams, 1999). River discharge of freshwater into Florida Bay was measured by USGS for all significant input locations (USGS, 2005). Daily average discharges for 2001 were provided by C. Hittle, USGS (not shown). Measurement locations are shown on Figure 1. Subtidal time series of all current, transport, sea level, and wind data sets were computed using a 40 hour low-pass (HLP) Lanczos filter to remove tidal, sea breeze, and inertial fluctuations to better understand low-frequency variations.

Results

Along-Channel Currents and Volume Transport.—The ensemble averages of shipboard measured (ADCP) transports (*Qa*) and standard deviations for the Twisty and Topsy sections show robust estimates of the average flows at the Topsy section with standard deviations generally less than ± 10 $m^3 s^{-1}$ (Fig. 3). Although standard deviations are higher at the Twisty section (ranging from ± 10 to 50 $m^3 s^{-1}$), the mean flows are still well-resolved, being considerably larger than the standard deviations in all but two cases. The standard deviations are a combination of measurement error plus real transport variability. If we assume equal weight to each, then measurement error is 13 $m^3 s^{-1}$ at Twisty and 5 $m^3 s^{-1}$ at Topsy. The smaller cumulative error at Topsy is reasonable because the channel width is about half that at Twisty and water depths are slightly deeper and more consistent across the channel, causing fewer dropouts of current profiles. Volume transports ranged from −34 $m^3 s^{-1}$ to +29 $m^3 s^{-1}$ at Topsy and −98 $m^3 s^{-1}$ to +103 $m^3 s^{-1}$ at Twisty over the wet season (Fig. 3). Negative transports represent channel flow out of the basin and positive values are inflows.

First order statistics of along-channel currents providing water exchange to WB are given in Table 1. Currents were strongest and most variable (± 20 cm s^{-1} SD) in Dump and Crocodile channels, due to the narrow channel widths. In contrast, standard deviations of currents in the much wider Twisty and Topsy channels were

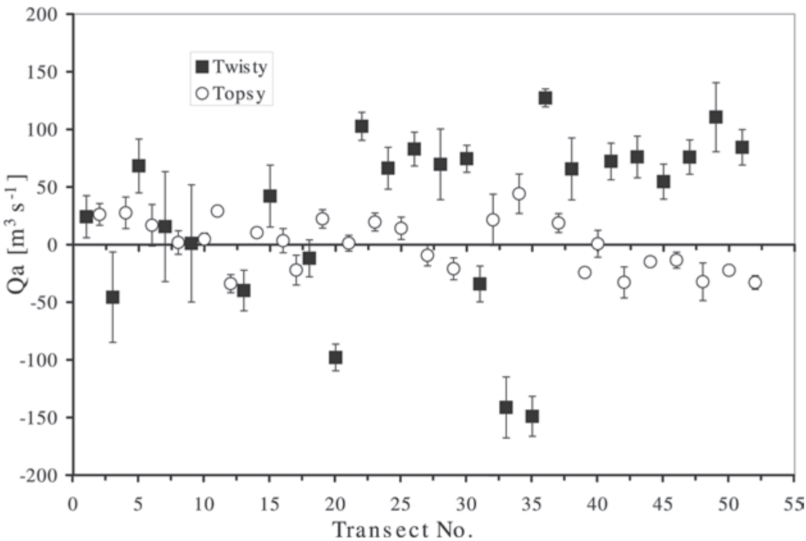

Figure 3. Ensemble averaged volume transports (± SD) at Twisty and Topsy transects in Whipray Basin, measured with 4–6 shipboard ADCP sections per transect during the wet season of 2001.

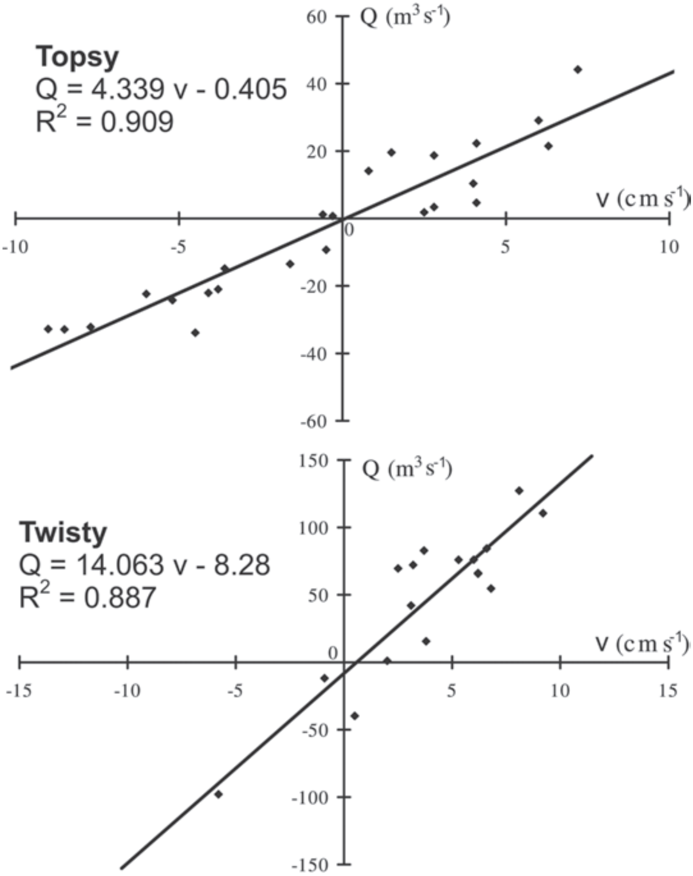

Figure 4. Linear regression of along-channel currents against volume transport measured with shipboard ADCP transects across the current meter sites at Topsy (top) and Twisty (bottom) transects during the wet season of 2001. Regression relationships were used to convert current to transport.

± 3 and 6 cm s^{-1}, respectively for both seasons. All channels showed some degree of semi-diurnal and diurnal tidal variability that tended to decrease with distance from the Gulf. Along-channel currents also revealed considerable sub-tidal variability at all sites.

Along-channel currents at Topsy and Twisty were converted to volume transport time series by applying linear relationships derived from regressing ensemble averaged transports from shipboard ADCP sections with moored current measurements (Fig. 4). Along-channel currents accounted for about 90% of the variance in the ADCP measured transports at both channels. At Topsy there was a positive slope of 4.3v and near zero bias, whereas at Twisty the slope was greater at 14.1v and the bias was near -8.3. Twisty is a much wider channel than Topsy and the non-uniform along-channel flows resulted in a slightly greater scatter about the fitted line and the non-zero bias. This bias represents only about 3% of the range of measured transports at Twisty and is considered non-significant. Volume transport variability for the major flow channels (Fig. 5, Table 2) is similar to that of the along-channel currents, as expected from the linear conversion. However, there are large differences in transport magnitudes with the wider channels (Topsy and Twisty) providing much larger

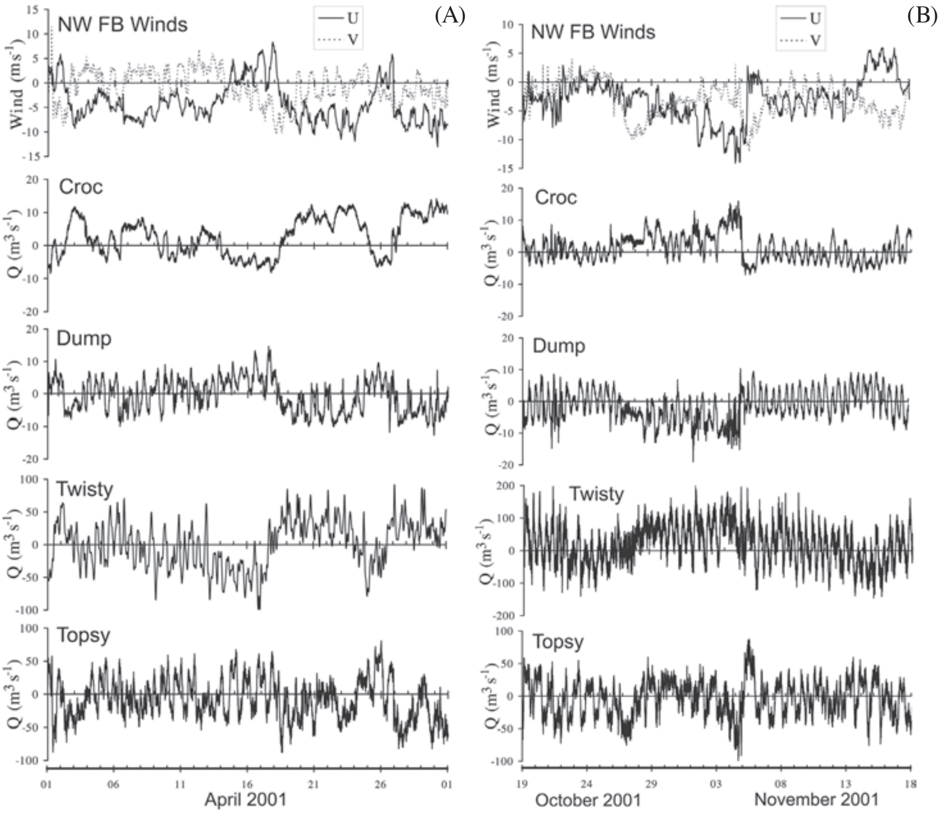

Figure 5. Three-hr low-pass filtered volume transports derived for the major flow channels to Whipray Basin for a 1-mo period from (A) the 3.5-mo total record of the dry season 2001 and (B) the 2.5-mo record of the wet season in 2001. Positive values are inflows and negative are outflows. Also shown are east-west (U) and north-south (V) wind components from the northwest Florida Bay SeaKeys site.

volume flows that typically varied from ± 50 to 100 $m^3 s^{-1}$ compared to ± 10 $m^3 s^{-1}$ for the more narrow Crocodile and Dump channels. These 1 mo views of transports and winds clearly show significant subtidal variations that have visual correlation between stations and with local wind forcing (see below). Approximately 60%–80% of the total wind variability occurred at subtidal frequencies, whereas 20%–80% of the total volume transport variability in the channels was due to subtidal motions (Table 2B). Transport variability was primarily due to subtidal motions at the Crocodile channel and a mixture of tidal and subtidal flows at the other channels.

Subtidal Transport Variations.—A highly coherent, out-of-phase relationship between subtidal transports at Crocodile and Dump is clearly observable during both seasons (Fig. 6). Inflows at Crocodile occurred simultaneously with outflows at Dump and visa versa. There also tended to be a similar relationship between transports at Twisty and Topsy, although these were not consistently 180° out-of-phase. These transport variations are consistent with fluctuations in local wind forcing, which is highly coherent over the south Florida region on time scales longer than 1 d (Lee and Williams, 1999). Westward winds (toward the west) are associated with inflows to WB through the eastern channels of Crocodile and Twisty and corresponding outflows through Dump and Topsy (Fig. 6). Throughout the year, the prevailing

Table 2. First order statistics of (A) 3-hr low pass (HLP) filtered along-channel transports ($m^3 s^{-1}$), and (B) 40 HLP along-channel transports ($m^3 s^{-1}$) from channels to Whipray Basin and northwest Florida Bay wind components ($m s^{-1}$) over record lengths during 2001 dry and wet seasons. For (B), percent of total variance due to subtidal variations is also provided.

A. 3 HLP along-channel transports ($m^3 s^{-1}$)

	Start m/d/h	End m/d/h	Data Pts	Mean	± SD	Max	Min	Range	Var.
Dry season									
Wind U	3/26/0000	7/20/0000	2,785	–2.6	3.9	9.9	–13.1	23.9	15.1
Wind V	3/26/0000	7/20/0000	2,785	0.1	3.2	11.5	–11.0	22.5	10.4
Crocodile	3/27/2105	6/04/1005	9,871	2.0	5.1	14.1	-9.1	23.1	26.1
Twisty	3/27/2105	7/19/0635	16,330	–11.5	48.9	229.5	–217.3	446.8	2391.8
Topsy	3/27/2105	7/19/0635	16,330	–3.1	26.9	93.0	–107.2	200.2	724.8
Dump	3/27/2105	7/19/0635	16,330	0.2	4.4	15.8	–12.6	28.4	19.0
Wet season									
Wind U	9/3/1500	11/19/1200	1,846	–2.7	3.6	12.1	–14.4	26.5	13.1
Wind V	9/3/1500	11/19/1200	1,846	–1.5	3.6	14.2	–12.0	26.2	13.0
Crocodile	10/14/1555	11/19/1200	10,322	1.2	4.0	16.0	–7.0	23.0	16.0
Twisty a	9/3/1800	9/30/0000	7,561	–26.2	60.9	325.0	–316.7	641.7	3706.0
Twisty b	10/15/0000	11/19/1200	10,225	21.6	67.4	229.5	–168.1	397.6	4545.7
Topsy	9/3/1500	11/19/1200	22,141	–5.0	26.1	123.1	–98.9	222.0	678.9
Dump	9/3/1500	11/19/1200	22,141	–0.6	4.9	25.2	–20.9	46.2	23.8

B. 40 HLP along-channel transports ($m^3 s^{-1}$).

	Start m/d/h	End m/d/h	Data Pts	Mean	± SD	Max	Min	Range	Var.	%Var. low-freq
Dry season										
Wind U	3/28/0000	7/19/1200	455	–2.7	3.5	6.3	–8.9	15.2	12.2	81.2
Wind V	3/28/0000	7/19/1200	455	0.1	2.5	7.8	–8.0	15.7	6.1	58.9
Crocodile	3/28/0000	6/04/1000	289	2.0	4.5	11.8	–6.1	17.8	20.4	78.0
Twisty	3/28/0000	7/19/1200	455	–9.0	25.8	54.6	–63.2	117.8	665.4	27.8
Topsy	3/28/0000	7/19/1200	455	–2.8	12.8	30.2	–57.5	87.7	164.5	22.7
Dump	3/28/0000	7/19/1200	455	0.2	2.8	6.7	–6.6	13.3	8.1	42.7
Wet season										
Wind U	9/3/1800	11/19/1200	308	–2.7	3.2	9.7	–11.0	20.7	10.1	76.8
Wind V	9/3/1800	11/19/1200	308	–1.5	3.1	10.0	–9.5	19.5	9.6	73.8
Crocodile	10/14/1800	11/19/1200	144	1.2	3.0	12.2	–5.4	17.7	9.3	57.9
Twisty a	9/3/1800	9/30/0000	106	–20.9	25.3	7.7	–134.3	142.0	641.3	17.3
Twisty b	10/15/0000	11/19/1200	143	19.7	33.4	101.2	–47.1	148.3	1119.	24.6
Topsy	9/3/1800	11/19/1200	308	–4.8	13.8	46.4	–52.6	99.0	191.5	28.2
Dump	9/3/1800	11/19/1200	308	–0.6	3.0	9.9	–9.3	19.2	9.2	38.7

winds tend to be from the east to southeast. However, during the winter/spring dry season these prevailing winds are interrupted by the passage of cold fronts, which cause a clockwise rotation of wind direction and increased speeds as the winds shift around to be from the west then north directions. Summer winds are generally weak and from the southeast, but become stronger and from the northeast in the fall. Winds toward the east (+U) or west (–U) can last several days and cause near simultaneous transports through Crocodile and Dump channels of ± 5–10 $m^3 s^{-1}$, and ± 30–60 $m^3 s^{-1}$ through Twisty and Topsy channels in alignment with the wind direction (Fig. 6). Linear regression analysis shows strong negative correlation between

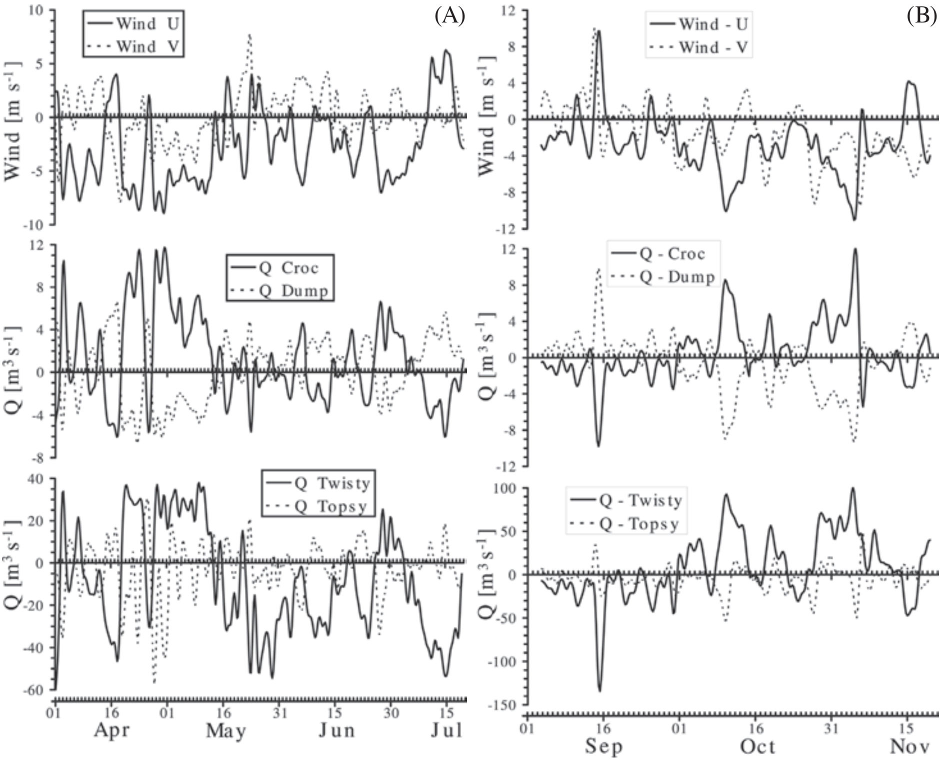

Figure 6. Forty-hr low-pass filtered northwest Florida Bay wind components and volume transports through Whipray Basin flow channels during the (A) dry season and (B) wet season of 2001. Positive values are inflows and negative are outflows.

the east-west wind component and transports to WB through Crocodile and Twisty and positive correlation for Dump and Topsy transports for both seasons (Fig. 7). The correlations are strongest for Crocodile, Twisty, and Dump channels where 70%–80% of the transport variance can be explained by east-west wind forcing. The Topsy channel is located at the southern end of WB, which provides considerable north-south fetch and results in a mixed response to both wind components. Transports were also regressed against wind stress components, but the correlations were much weaker than with the above wind components. Simply put, winds toward the west drive inflows to WB through the channels located on the eastern side of the basin and simultaneous outflows through channels at the western and southern boundaries of the basin. The opposite occurs for winds toward the east.

Salinity.—Representative surface salinity patterns for the entire Florida Bay from the monthly surveys during the 2001 dry and wet seasons are shown in Figure 8. Hypersalinity (> 40) first developed in the WB region of north-central Florida Bay in Mar, and then spread south and westward occupying a large portion of the central and western bay by the end of the dry season in Jul. Throughout the dry season the northeast basin region, which receives freshwater discharge from Trout Creek and Taylor River, maintained fresher conditions and only reached oceanic salinity levels (36) in Jul. As salinity increased in WB, large horizontal salinity gradients were established across the mud banks and north-south oriented mangrove islands (Black Betsy Keys lying just west of Taylor River; Fig. 1) that separate Whipray from lower

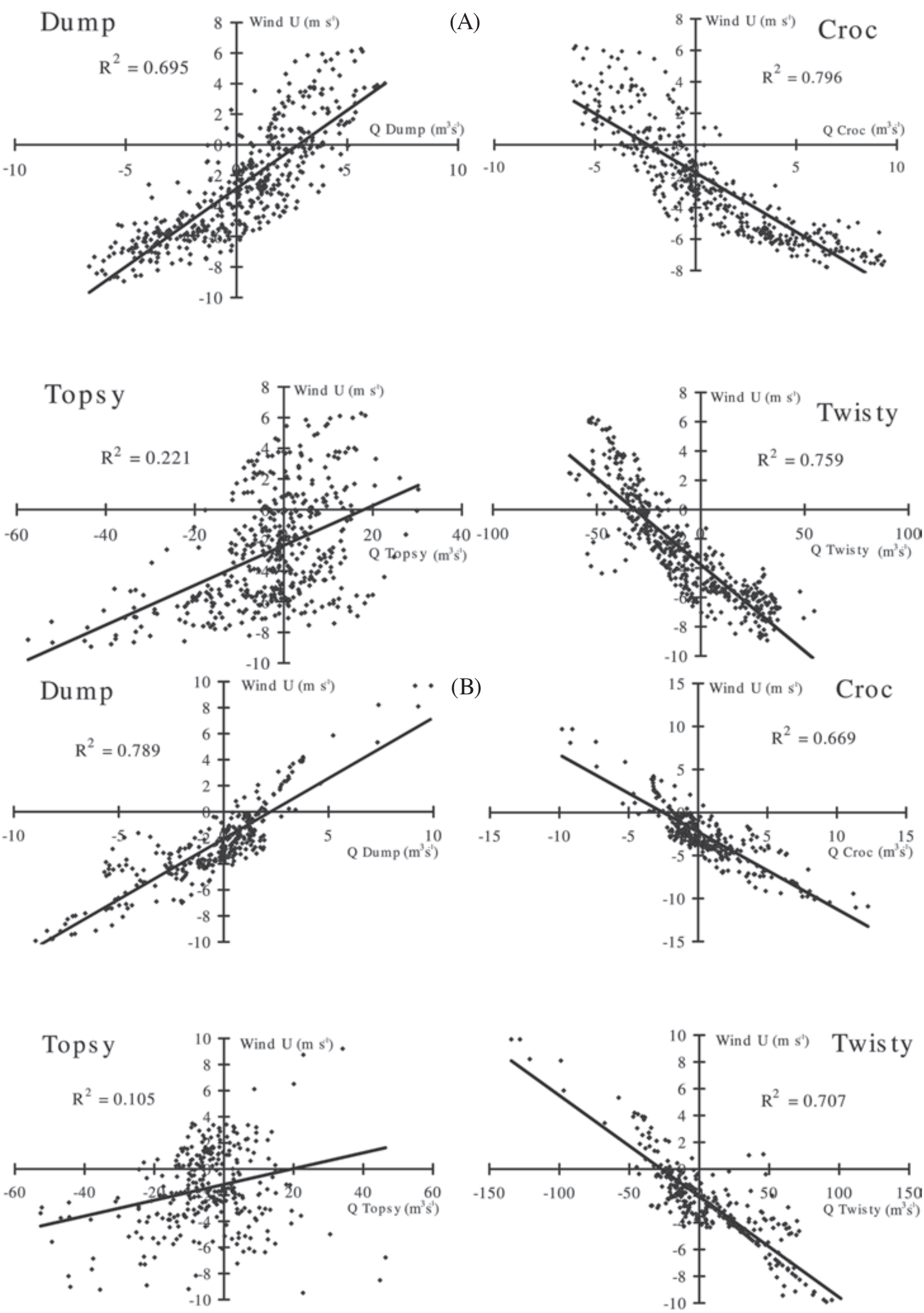

Figure 7. Linear regression between subtidal time series of east-west wind and transports through Whipray Basin flow channels during the (A) dry season and (B) wet season of 2001.

salinity waters in the northeast basin. Salinity in the western and southeast areas of the bay was also lower than in the central region due to dilution by Gulf and Atlantic nearshore waters, including transport of Shark River discharge along the western boundary of the bay (Nuttle et al., 2000; Johns et al., 1999; Wang, 1998). Enhanced exchange of Gulf and Shark River waters with the western basins tends to buffer the

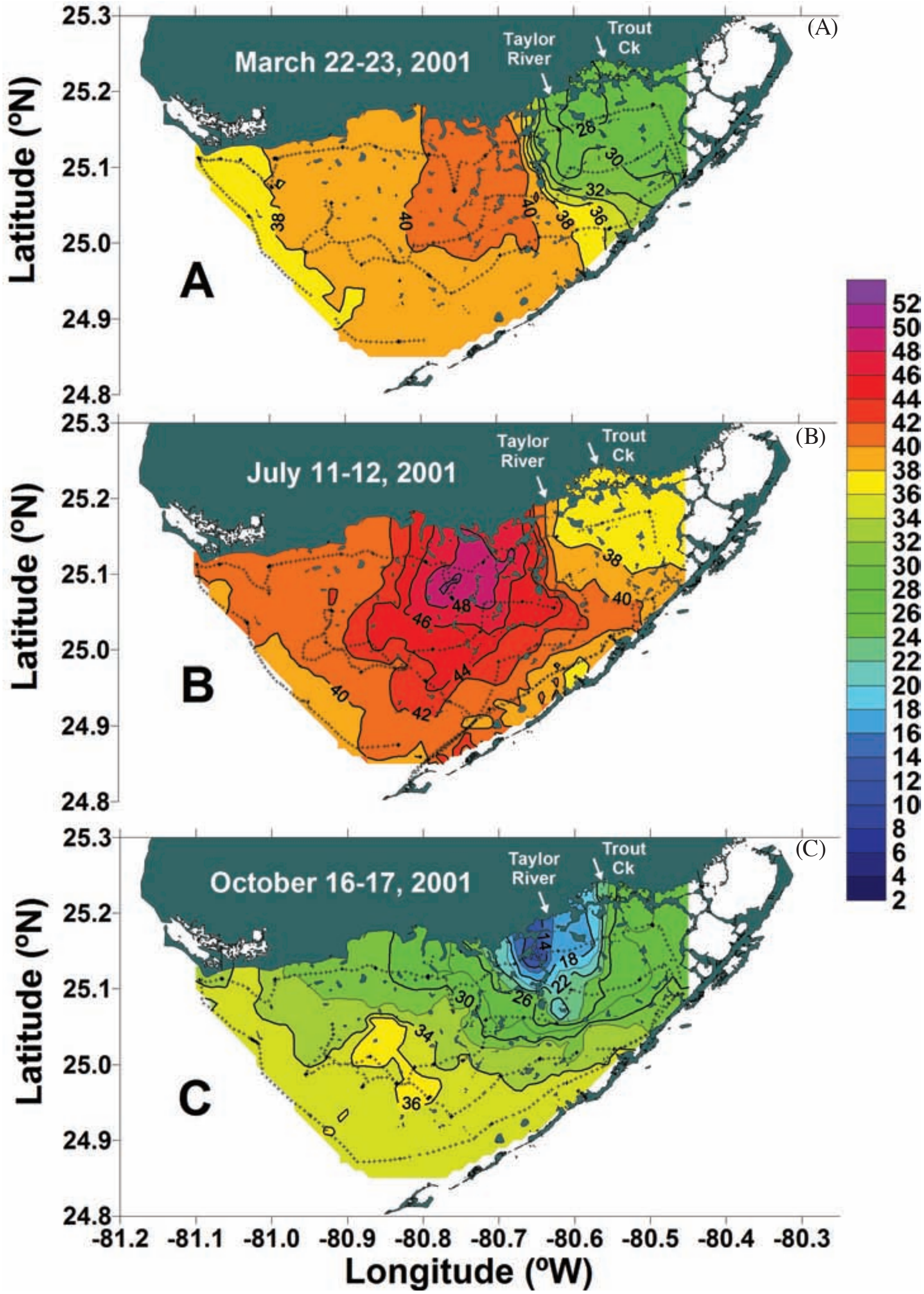

Figure 8. Florida Bay surface salinity from 2001 monthly surveys of the R/V VIRGINIA K using continuous underway measurement for: (A) Mar 22–23 dry season; (B) Jul 11–12 near the end of the dry season; and (C) Oct 16–17 wet season. Vessel track shown with dotted line.

development of hypersalinity in this region. During the wet season salinity dropped rapidly in the northeast basin, reaching a minimum in Oct of about 10 in the vicinity of Trout Creek and Taylor River discharges (Fig. 8). The fall salinity pattern shows a bay-wide decrease in salinity from increased rainfall. A north-south gradient with

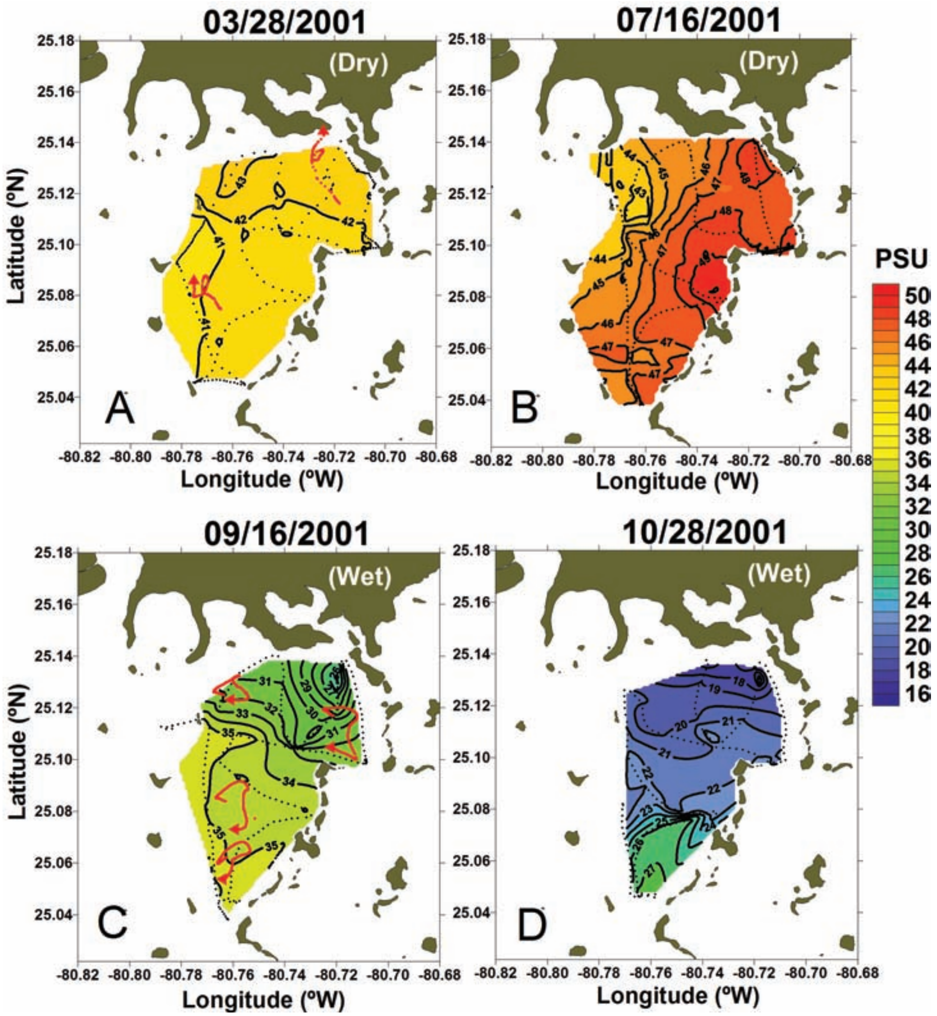

Figure 9. WB surface salinity from high-resolution surveys of the R/V VIRGINIA K using continuous underway measurement for (A) Mar 28 dry season, (B) Jul 16 near the end of the dry season, (C) Sept 16 wet season, and (D) Oct 28 near the end of wet season 2001. Vessel track shown with dotted line. Surface drifter trajectories shown with red arrows.

fresher water to the north indicates increased runoff and possibly greater rainfall near the northern upland border of the bay. Salinities along the western and southeastern regions of the bay showed the smallest seasonal change due to the buffering effect from exchange with Gulf and Atlantic waters. Salinity profile data (not shown) indicate that basin interiors were well mixed vertically, most likely a result of the shallow depths (< 3 m) and local wind mixing. The lack of stratification indicates that vertical mixing through currents, winds, and diurnal cooling is sufficient in these extremely shallow basins to overcome the tendency to develop gravitational circulation from horizontal salinity gradients (Fig. 8). Also, the largest horizontal salinity gradients developed over the mud banks separating interior basins where depths are typically < 30 cm and tidal currents are more pronounced then within basin interiors.

High spatial resolution salinity surveys of WB made throughout the dry and wet seasons of 2001 concentrated on the north central region of the bay (see representa-

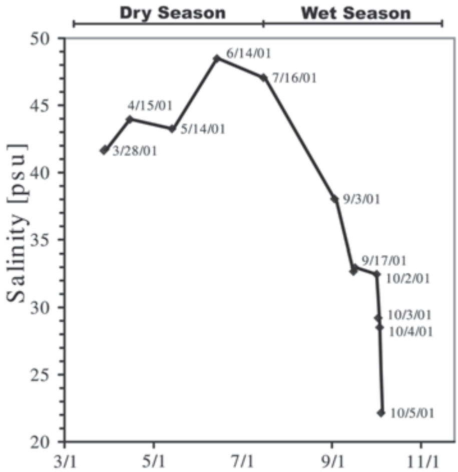

Figure 10. Time series of basin average salinity for Whipray Basin during dry and wet seasons of 2001 from R/V Virginia K spatial surveys.

tive surveys in Fig. 9 and time series of basin average salinity in Fig. 10). At the start of the dry season, basin salinities were already above 40 with highest values near 43 found across the northern third of the basin and near 41.5 in the southern end (Fig. 9A). The lowest salinities in the Mar survey were observed along the basin's western boundary at < 41. Water circulation determined from 2-d drifter trajectories during this period showed a general drift pattern toward the north-northwest that tended to follow the wind direction with an average drift speed of a few cm s^{-1}. As the dry season progressed, the mean basin salinity increased at a rate of about 2.6 mo^{-1} from 41.6 on Mar 28 to a maximum of 48.5 on Jun 14 (Fig. 10). During this period of increasing salinity the highest values were found in the north and along the eastern boundary of the basin. The seasonal shift to decreasing basin salinities began with intrusions of lower salinity water along the northwestern boundary near the Dump Keys (Fig. 9B). This resulted in a positive east-west salinity gradient with salinity of 49 in the east and 43 in the western side of WB during Jul. As the wet season continued, low salinity intrusions occurred in the northeast region of the basin near McCormick Creek as well as in the northwest part of WB (Fig. 9C), causing the salinity pattern to shift to a negative north-south gradient with minimum values near 25 in the north and maximum around 35 in the southern portion of the basin. Basin circulation continued to follow local wind patterns, which showed a clockwise rotation over the 2-d drifter trajectories of Sep 16–18 (Fig. 9C). The negative north-south salinity gradient was maintained through the wet season with similar magnitude, but with a widespread decrease in salt concentration. Near the end of the wet season in Oct salinity throughout the basin had decreased more than 20 and the basin average salinity decreased by 26.3 to a minimum value of 22.2 (Fig. 9D). The rate of decline in basin average salinity was −5.8 mo^{-1} for the wet season, which was more than twice the rate of salinity increase in the dry season. The largest change in basin average salinity occurred in Oct when a drop of 10 occurred over 3 d from the influence of a tropical storm.

Freshwater Discharge.—The largest freshwater discharge to Florida Bay occurred at Trout Creek, which discharges into the northeast (NE) basin through the

Table 3. Seasonal average volume transport (*Q*), salinity (*S*), and salt flux (*Q'S'*) from 40-hr low pass (HLP) filtered moored time series for 2001. 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).

Station	*Q* ($m^3 s^{-1}$)	± SE ($m^3 s^{-1}$)	*S*	± SE	*Q'S'* ($m^3 s^{-1}$)	± SE ($m^3 s^{-1}$)
Dry season						
Croc	1.2	0.6	no data			
Twisty	–9.0	3.4	44.83	0.9	–31.8	12.7
Topsy	–2.8	1.7	44.56	0.4	–2.9	3.3
Dump	0.2	0.4	44.19	1.1	–6.5	1.0
Net	–10.4					
Wet season						
Croc	0.4	0.5	23.96	1.8	–8.9	1.1
Twisty	8.2	4.7	28.38	1.7	–100.2	14.1
Topsy	–4.8	2.2	32.65	1.5	–1.2	6.4
Dump	–0.6	0.5	27.33	1.5	6.8	1.0
Net	3.2				–109.5	

mangrove enclosed Joe Bay on the northern boundary (Fig. 1). Weak, but significant discharges to the NE Basin occurred at Taylor River and Stillwater at the northeastern mangrove fringe. The only direct discharge to WB occurred through McCormick Creek at the northeast mangrove boundary of the basin. The south Florida dry-wet seasonal cycle is clearly evident in the discharge data (not shown). There was no direct flow of freshwater to WB during the dry season, which continued through the winter/spring and early summer until mid-Jul. During this period, Trout Creek flow to the NE basin consisted of several day inflow and outflow events that were related to local wind forcing rather than discharge (Hittle and Poole, 2003). Wet season discharges began abruptly in mid-Jul and continued through the end of Nov. Daily discharge from Trout Creek during the wet season typically ranged from 20 to 30 $m^3 s^{-1}$. One larger event reaching near 55 $m^3 s^{-1}$ also occurred, as well as several flow reversals. Daily discharge to WB through McCormick Creek ranged from 2 to 10 $m^3 s^{-1}$.

Seasonal Mean Channel Flows and Salt Flux.—Examination of seasonal average channel flows (*Q*), salinity (*S*), salt flux (*Q'S'*) and their standard errors (Table 3) show that the seasonal means are generally well-resolved with the standard errors either much less or approximately equal to the means. The only exception was for the salt flux at Topsy, where the standard error was larger than the very weak mean flux during the wet season. During the dry season there was a mean outflow at Twisty and Topsy and a weak inflow at Crocodile and Dump. Mean salinities at all measurement sites were near 44 and there was a flux of salt out of the basin with the transport of higher salinity water within WB out of the basin through the eastern channels and lower salinity water into the basin through Dump channel in the west. This salt flux would tend to freshen the basin and help to reduce hypersalinity development in the dry season when evaporation exceeds precipitation. Unfortunately, the conductivity sensor at Crocodile did not function properly and no salinity time series are available for this period. During the wet season there was a mean inflow at Twisty and outflow at Topsy. The mean inflow at Crocodile was nearly balanced by mean outflow at Dump (Table 3). Mean salinities were lower at the northern sites, reflecting a mean negative north-south salinity gradient during the wet season. There was a large negative salt flux at Twisty of −100.2 $m^3 s^{-1}$ indicating a mean inflow of fresher water at this site in the wet season, consistent with the salinity survey data. There was also a weaker inflow of fresher water at Crocodile that was nearly balanced by an outflow of lower salinity water at Dump (Table 3). At Topsy, the salt flux was negligible, similar to that of the dry season.

Water Balance.—Direct measurement of water exchange between Florida Bay interior basins is a daunting task. Individual basins within the bay's interior are surrounded by shallow, expansive mud flats with dense sea grass beds and uncertain depths (Fig. 1). Most of the connecting channels are too shallow for installation of current meters. At the only four locations where we could make current meter measurements, significant reversing flows occurred at tidal and local wind forced time scales (generally < 2 wks) and during transient tropical storms. From current time series at these four sites, we can estimate seasonal mean flows and their influence on net water exchanges and residence times for WB. However, to estimate the total water balance for WB, we must know its total change in water volume over time, $\partial V_{WB}/\partial t$, which equals the total flow, Q_T, into or out of WB, and must balance the sum of the flows through the four measured channels, Q_c, plus the flows over the banks and any small channels that were not measured, Q_b, written as:

$$\partial V_{WB}/\partial t = Q_T = Q_c + Q_b \tag{1}$$

Changes in sea level were measured at 17 stations throughout Florida Bay as part of the ENP monitoring network (Fig. 1). These data were filtered to produce subtidal time series and analyzed together with local winds, showing a coherent, in-phase response of sea level to local wind forcing over the entire bay. The largest sea level changes occurred in the northern portion of the bay for wind directions that aligned with the bay's major axis (oriented toward 50° and 230° T) and indicate a simple set-up or set-down response of sea level to winds toward the northeast or southwest, respectively. Sea level increases and decreases reached up to 40 cm for these up-bay and down-bay wind events, but more typical variations had standard deviations of about ± 10 cm. The strong correlation in sea level among stations allowed us to use optimal spatial interpolation with Surfer software to derive gridded fields of sea level for each 12 hr time step (see Fig. 11 for representative contour plots of the bay sea level fields during a sequence of fall wind events that tended to align with the bay's principal axis). These gridded sea level fields were then used to compute sea level changes for the interior of WB, which were subsequently converted to total volume changes per time step or $\partial V_{WB}/\partial t$. Using equation (1) above, and knowing the total flow (Q_T) and the channel flow (Q_c), we computed the flow over the banks and small ungauged channels (Q_b). The resulting total flows, Q_T, into and out of WB indicate that during the dry season total flow events reached ± 100 $m^3 s^{-1}$, but more typical events ranged over ± 50 $m^3 s^{-1}$ (Fig. 12). During the wet season it was common for total flow events to reach ± 100 $m^3 s^{-1}$. The total channel and bank flows tend to be out of phase and near equal in magnitude. Along-axis winds are strongly correlated with the total bank flows (r^2 =0.6 for both seasons) and nearly in-phase. Along-axis winds toward 50° T or 230° T caused net inflows or outflows, respectively, over the banks that reached ± 100 $m^3 s^{-1}$, but events typically ranged over ± 50 $m^3 s^{-1}$ for the

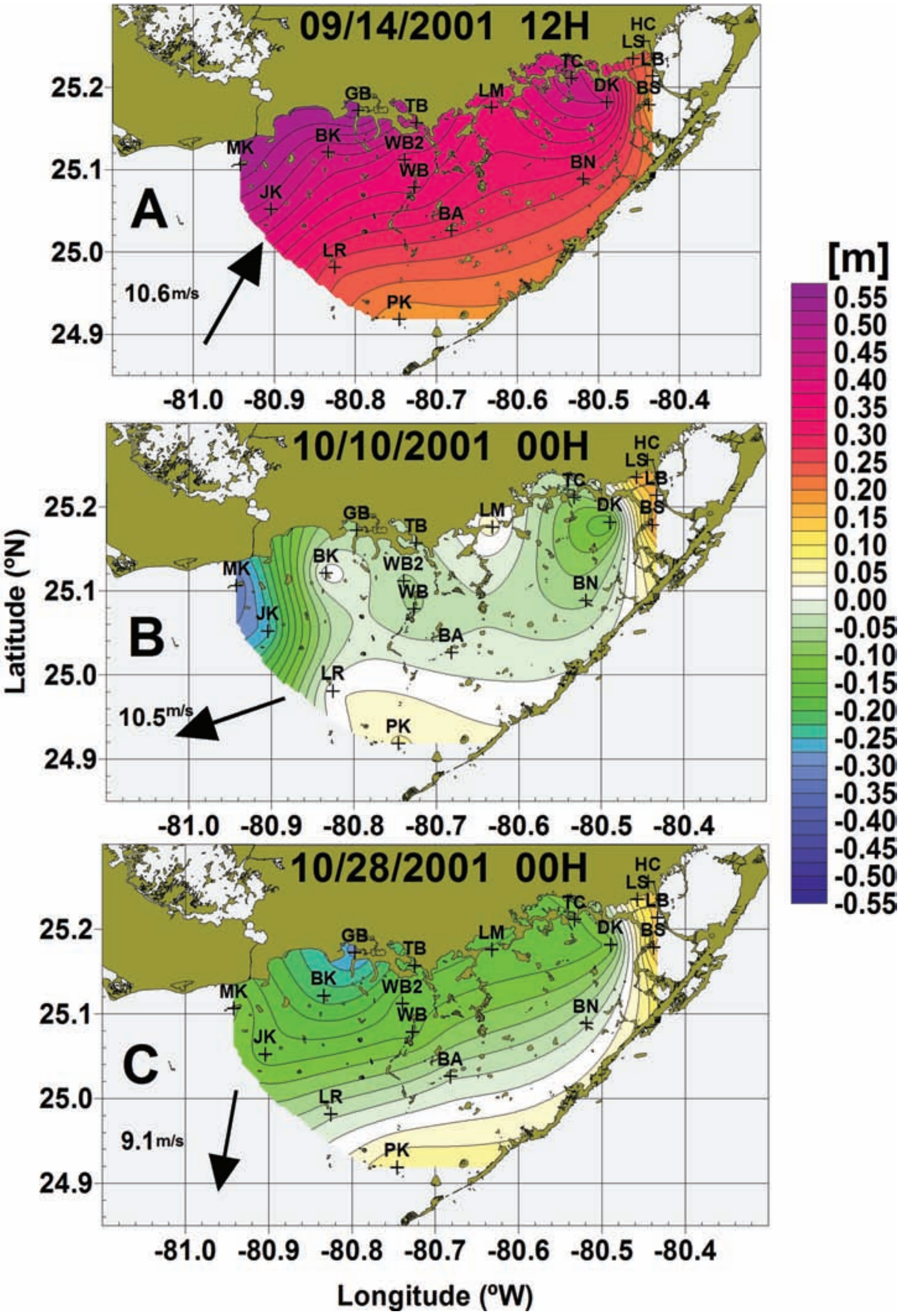

Figure 11. Gridded and contoured sea level fields derived from the Everglades National Park monitoring array using Golden Software surfer interpolation for fall 2001 wind events. Winds from the northwest Florida Bay SeaKeys station are shown with black arrows.

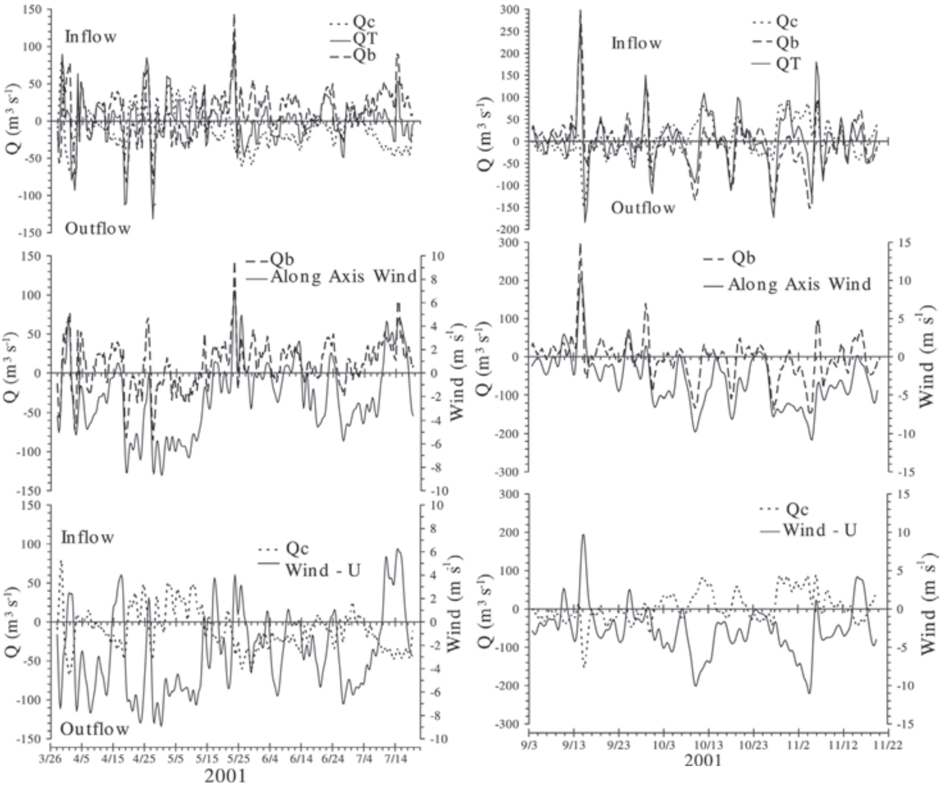

Figure 12. (A) Dry and (B) Wet season 2001. Subtidal time series of (upper panel) total flow (Q_T), total channel flow (Q_c) and total bank flow (Q_b), (middle panel) total bank flow plotted with along-axis winds, and (lower panel) total channel flow plotted with east-west wind component (U, no rotation) (bottom panel). (B) Subtidal time series of (upper panel) total flow (Q_T), total channel flow (Q_c) and total bank flow (Q_b), (middle panel) total bank flow plotted with along-axis winds, and (lower panel) total channel flow plotted with east-west wind component (U, no rotation).

dry season. Bank flow events were about a factor of two larger during the wet season, even though wind speeds were similar in both seasons. This is consistent with the observed seasonal increase in mean water level of about 30 cm in fall associated with large-scale warming of oceanic waters of the southwest North Atlantic. A plot of total channel flow with the east-west component of the wind (Fig. 12, lower panel) reveals that these winds are significantly correlated and out of phase with the channel flow ($r^2 = 0.5$ in the dry season and 0.6 in wet season). Winds toward the west (–U) occur with net inflow through the measured channels and winds toward the east (+U) are associated with net outflows, reaching ± 50 $m^3 s^{-1}$ during the dry season and near ± 100 $m^3 s^{-1}$ for the wet season.

Residence Times.—On seasonal time scales, the average total flow is approximately zero and there is a near balance between mean channel flow and bank flow as would be expected from Eqn. 1 when $Q_T = 0$ (Table 4). During the dry season there was a mean inflow to WB over the banks and a near matching mean outflow through the measured channels due to winds toward the east that occurred with cold front passages. The mean volume of WB is estimated at 56.5 × 10^6 m^3 (mean depth 0.65 m × surface area 86.9 km^2) and assuming this is constant, a mean throughflow of 11 $m^3 s^{-1}$ would take approximately 2 mo to exchange an equivalent water volume. Dur-

Table 4. Seasonal and annual means of total transport (Q_T) from Whipray Basin sea level monitoring data, 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 2001.

Transport	Dry season	Wet season	Annual mean
Q_T	0.8	–0.1	0.4
Q_c	–10.5	3.2	–3.6
Q_b	11.2	–3.3	3.9
Basin renewal time: (mo)	2.0	6.7	5.8

ing the wet season, winds toward the west and southwest produced a mean outflow over the banks balanced by a mean inflow through the deeper measured channels. A mean throughflow of 3 $m^3 s^{-1}$ requires 6.8 mo to exchange the WB mean volume. With an annual mean exchange rate of 3.9 $m^3 s^{-1}$, over annual time scales the volume of WB could renew in approximately 6 mo.

Alternatively, total flow can be expressed in terms of the sum of the seasonal water balances for WB. This can be written in terms of the sum of the contributions from important known physical processes, a seasonal water balance approach:

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

where Q_w is the total transport due to local wind forcing, Q_g is the unknown ground water inflow to WB, r is river discharge to WB measured by USGS at McCormick Creek, P is precipitation measured by the ENP monitoring array, E is evaporation determined from several different approaches (Nuttle et al., 2003) and Q_T was determined above (Eqn. 1 and Table 4). Q_w consists of the sum of the net wind-driven flows over the banks, Q_{wb}, plus the combined wind forced flows through the channels, Q_{wc}, given as:

$$Q_w = Q_{wb} + Q_{wc} \tag{3}$$

where Q_{wb} is derived from linear regression with the along-axis rotated winds and Q_{wc} is derived from linear regression with the east-west component of the winds (U). These regressions (not shown) were made for both the dry and wet seasons and indicate that wind forced flows account for about 60% of the total channel and total bank transport variations with r^2 values of 0.6 (see also Figs. 12A and B).

Seasonal averages of volume transport contributions from all the physical processes contributing to the WB water balance are given in Table 5, with ground water input derived as required to balance the other terms. During the dry season wind-driven flows tend to compensate with 11.2 $m^3 s^{-1}$ inflow over the banks nearly balanced by –10.5 $m^3 s^{-1}$ outflow through the channels, and providing the dominant flushing of interior waters with a two month renewal time. Any offset in wind-driven flows was accounted for by the small total transport of 0.8 $m^3 s^{-1}$. This leaves the combined freshwater inputs of $r + P + E$ to compensate for a weak ground water input estimated at 1.7 $m^3 s^{-1}$ inflow. In the wet season, the direction of the mean wind-driven flow is reversed, with an average inflow of about 3.2 $m^3 s^{-1}$ through the combined channels and a corresponding outflow over the banks of –3.3 $m^3 s^{-1}$ that provided a weak exchange of interior waters, and a basin renewal time of 6.8 mo. Groundwater flow for

Table 5. Values for annual water balance model during wet and dry seasons of 2001 (in $m^3 s^{-1}$).

	Q_w	$+ Q_g$	$+ r$	$+ P$	$+ E$		Q_T
Dry	0.8	1.65	–0.5	3.07	–4.25	=	0.77
Wet	–0.07	–4.67	3.5	4.81	–3.64	=	–0.07
Annual average	0.36	–1.51	1.5	3.94	–3.94	=	0.35

the wet season was again required to balance the remaining freshwater terms ($r + P + E$), resulting in a mean downwelling of $-4.7\ m^3 s^{-1}$.

Annual contributions to the water exchange in WB were determined by averaging the dry and wet season values (Table 5). The annual means suggest that precipitation tends to balance evaporation, and a weak contribution of basin water to groundwater occurred at a rate of $-1.5\ m^3 s^{-1}$ that balanced the mean annual river discharge through McCormick Creek. In other words, the freshwater sources are in balance over the year, including a weak contribution of WB water to ground water, leaving a small residual average wind-driven flow to compensate the insignificant annual mean water exchange of $0.4\ m^3 s^{-1}$.

Salt Balance.—An alternative method for estimating water renewal rates and residence times can be applied to WB by combining the equations for the conservation of volume and salt. This is an indirect salt balance approach, by which the volume exchange rate of inflowing ocean waters to WB can be estimated as that required to produce the observed seasonal changes in basin average salinity, given the amount of freshwater flux to the water body. Volume conservation for WB on seasonal time scales assumes that the total flow in and out of the basin must balance. This balance is given as:

$$Q_i + r + P = Q_o + E \tag{4}$$

where Q_i is the inflow of water from basins surrounding WB, Q_o is outflow of water from WB, and r, P and E are as given previously and summarized in Table 5. Using $R = r + P - E$ for the net supply of freshwater and substituting into Eqn. (4) yields:

$$Q_o = Q_i + R \tag{5}$$

Likewise, salt conservation for WB requires that the salt transport into WB must balance the salt transport out of the basin:

$$S_i Q_i = S_o Q_o \tag{6}$$

where S_i and S_o are respectively, the average salinity of the inflow and outflow waters. For seasonal changes in WB spatial average salinity, S_{WB} (Fig. 10), the salt balance equation is written as follows:

$$V_{WB}\, \Delta S_{WB} / \Delta t = S_i Q_i - S_o Q_o \tag{7}$$

where V_{WB} is the mean volume of WB. Substituting Eqn. (5) into Eqn. (7) and reorganizing gives the fractional rate of exchange of WB mean volume by inflowing waters Q'_i:

$$Q_i' = (\Delta S_{WB}/\Delta t + S_o R')/(S_i - S_o) \quad (8)$$

where $Q'_i = Q_i / V_{WB}$ and $R' = R / V_{WB}$. From the basin fractional exchange rate we can estimate the time, T, in months required to renew a volume equivalent to the mean volume of WB or the residence time:

$$T = 1/Q_i' \quad (9)$$

The estimated fractional exchange rates and residence times for WB during dry and wet seasons are given in Table 6, along with the necessary input values for the salt model (Eqn. 8). During the dry season the mean basin salinity increased at a rate of 2.6 mo^{-1}, which caused salinity inside the basin to increase from 2 to 3 greater than the surrounding waters. The estimated exchange rate of 0.4–0.3 mo^{-1} and renewal times of 2.5–3.4 mo agree well with direct estimates from the water balances given above for the dry season and in Table 4. The water balance estimates also indicate that the primary flushing mechanism was wind-driven inflow across the western banks, balanced by outflows through the eastern and southern channels of Twisty and Topsy, respectively. This explains the negative mean salt flux at the eastern channels (Table 3) as higher salinity WB waters are being exported from the basin through these channels during the dry season when the stronger wind events are toward the east. With the sudden onset of the wet season there was a rapid drop in basin average salinity of −5.8 mo^{-1}. The major flushing mechanism was wind-driven inflow through the eastern channels and outflows over the western banks. The inflow was primarily through Twisty Channel, where lower salinity waters were transported into WB from the northeastern basins that received most of the local river discharge (Figs. 8 and 9) and resulted in a strong negative salt flux (Table 3). As previously mentioned, a large negative salinity gradient occurred across the shallow bank separating WB from the northeast basins (Figs. 8C and 9D). Salinity of these inflow waters was about 4.3 lower than outflow waters measured at Topsy Channel, and resulted in a negative inflow exchange rate of −0.3 mo^{-1}, which is equivalent to an outflow exchange rate and an exchange time scale of about 3 mo, a factor of two less than estimated from water balances for the wet season.

Discussion

Long-term salinity observations show that the only area of Florida Bay where persistent hypersalinity occurs repeatedly during the dry season is the north-central region, with maximum values normally found in the area of WB (Boyer et al., 1999;

Table 6. Terms used in the salt balance model (Eqn. 8) for estimating the fractional rate of volume exchange (Q'_i mo^{-1}) and water renewal time (T) for Whipray Basin during dry and wet seasons 2001.

Season	$\Delta S_{WB}/\Delta t$ (mo^{-1})	R' (mo^{-1})	S_i	S_o	Q'_i (mo^{-1})	T (mo)
Dry	2.6	–0.078	42.7–41.7	44.69	0.44–0.3	2.3–3.4
Wet	–5.8	0.22	28.38	32.65	–0.32	3.1

Orlando et al., 1998; Nuttle et al., 2000). C. Kelble et al. (NOAA/AOML, unpubl. data) analyzed a 7-yr record of Florida Bay salinity patterns acquired from monthly surveys using continuous measurement along the vessel track from Jan 1998 to Jan 2005. Averaging salinity over each of the four sub-regions of the bay (northeast, north central, southeast and west), Kelble et al. (unpubl. data) found that the north-central region consistently had the highest dry season salinity except during the weak El Niño of 2002–2003, when higher rainfall combined with the shallower depths of the north-central region caused salinity to be lower compared to the south and west regions. Kelble et al. also found that a maximum regional average salinity of 46 occurred in the north-central region at the end of the 2001 dry season. Other regions of the bay had lower salinity than the north-central region in 2001 because of either having received significant river discharge (northeast region), having had sufficient exchange with Atlantic coastal waters through the passages between the Keys (southeast region: Smith, 1994; Smith, 1998; Lee and Smith, 2002), or having had adequate exchange with the Gulf of Mexico to preclude development of high salt concentrations (western region: Nuttle et al., 2000; Kelble et al., NOAA/AOML, unpubl. data). A long-term mean flow of 1000–2000 $m^3 s^{-1}$ is directed toward the Florida Keys past Cape Romano, the Ten Thousand Islands, and along the western boundary of Florida Bay, and eventually enters the reef tract of the Atlantic coastal zone through the Keys passages (Lee et al., 2002). This flow is driven by a mean Gulf to Atlantic sea level slope set up by a combination of oceanic (Loop Current/Florida Current) and wind induced processes. The mean southeast flow serves to entrain and transport discharge from rivers along the southwest Florida coast and Ten Thousand Island region of the Everglades toward the western boundary of Florida Bay and on to the Keys. The combination of river discharge with preferred alongshore mixing forms an inshore band of low-salinity water that can stretch from Tampa to Florida Bay (Johns et al., 1999). Surface drifters deployed in the Shark River discharge plume show a seasonal pattern of movement toward western Florida Bay and the Keys during the winter and spring dry season (Lee et al., 2002). Exchange with these lower salinity Gulf waters provides a moderating effect for western Florida Bay salinity, which helps to limit the development of hypersalinity in this region.

The wide, shallow mud banks and mangrove islands surrounding WB provide an effective barrier to water exchange with nearby areas of lower salinity to the east, south and west. During the dry season of 2001, when rainfall and river run-off were essentially zero, the WB average salinity increased by 2.6 mo^{-1} to reach a maximum of 48.5 in mid Jun while salinities in the adjacent regions were 6–8 lower. The primary mechanism found for regulating this water exchange was the local wind-driven transport. The response of waters within Florida Bay and its interior basins appears to be a simple set-up or set-down of sea level from local winds directed into or out of the bay, respectively. This response is similar to the dynamic response of sea level along a straight coastline to onshore or offshore winds (Csanady, 1982). Since the bay is only open to the west, winds toward the east tend to fill the bay, and westward winds cause a loss of interior waters and drop in sea level. Filling or emptying of each interior basin takes place by flow through the channels and over the shallow banks. Since both the basins and banks are quite shallow, wind-induced currents are directed downwind. In addition, sea level differences may be set up across the shallow banks that can also add to the direct wind-induced currents in the channels. Likewise, the greater friction in the extremely shallow waters of the banks will tend to reduce current speeds relative to flow in the channels. The net effect of these bank and channel flows is to produce a rise or fall of sea level within the basins that corresponds to the change in total flow, Q_T. Time series of total flow to WB show typical events of ± 50–100 $m^3 s^{-1}$, with durations of several days. Winds toward the east during cold front passages resulted in inflows over the banks that were balanced by outflows through the channels. Winds toward the west following the cold front passage produced the opposite flow condition with inflows through the measured channels and outflows over the banks. The net effect of the wind-driven exchange during the dry season was to produce a mean through flow of about 11 $m^3 s^{-1}$ with a net inflow over the banks balanced by a net outflow in the channels that would replace the volume of WB interior waters in about 2 mo. It is not uncommon for these wind-driven flows to last up to 8 d, with mean transports of 25 $m^3 s^{-1}$. Using the conversion for WB volume transport to mean sea level change of 1.0 $m^3 s^{-1}$ = 3.0 cm mo^{-1}, a mean transport of 25 $m^3 s^{-1}$ would cause a sea level change of 75 cm mo^{-1} or 20 cm in 8 d, which is about 30% of the WB mean depth. Therefore, a sequence of 4 or 5 such transport events during the dry season could exchange the mean volume of WB and account for a mean renewal time of 3 mo. By determining that the total volume flow (Q_T) to WB was primarily wind-induced, it was possible to use the seasonal water balances to derive estimates for the magnitude of ground water inflow. For the dry season, a weak groundwater input of about 1.7 $m^3 s^{-1}$ is necessary to balance the net loss of freshwater from the imbalance of freshwater flux term S.

With the onset of the wet season in Jul 2001, there was a rapid drop in mean basin salinity of −5.8 mo^{-1}, and negative north-south and east-west salinity gradients, indicating that the basin freshened more quickly in its northern and eastern parts. This pattern of freshening suggests a combination of freshwater inputs from: (a) McCormick Creek in the northeast; (b) greater rainfall near the mainland; and (c) exchange with the northeast basin through the Twisty section. Wind events toward the southwest during the period resulted in a mean through flow of 3 $m^3 s^{-1}$, with an inflow of lower salinity waters through the eastern channels and outflow over the western banks, that could exchange the WB mean volume in 6–7 mo. Wind-driven transports during the wet season occurred as a sequence of events, which lasted 3–4 d with mean through flows of about 50 $m^3 s^{-1}$, which could cause a sea level change of 150 cm mo^{-1} or 5 cm d^{-1}. Sea level variations of 5 cm d^{-1} are commonly observed in WB from the ENP monitoring data (not shown). For an event with a 3-d duration, sea level could change by 15 cm, which is equivalent to 23% of the mean volume of WB. Thus, the occurrence of four or five transport events of this type could renew the interior waters of the sub-region over the wet season, which would again account for a mean renewal time of 3 mo. Interestingly, an outflow of groundwater from the basin of −4.7 $m^3 s^{-1}$ was required to balance the increased net freshwater input. This reversal of groundwater flow may have resulted from the combined influence of greater freshwater input from river flow and precipitation, along with the higher sea level of the fall wet period. Negative groundwater flow is routinely observed following the dry season at the USGS Taylor River monitoring site upstream of Florida Bay (C. Hittle, USGS, pers. comm.). Seasonal and annual water balances show that groundwater inputs can be computed directly from the balance of freshwater flux terms: $Q_g \sim R = r + P + E$ from Eqn. 2 since $Q_T \sim Q_w$, and where the sign of the terms indicates inflow (+) or outflow (–) from the basin. The uncertainty of the groundwater estimate results from the uncertainties associated with determining seasonal averages of runoff, precipitation and evaporation, which combined are roughly estimated at about ± 3 cm mo^{-1}. Therefore, the uncertainty associated with seasonal estimates of groundwater inputs to WB is approximately ± 1 $m^3 s^{-1}$ and provides added confidence in our finding of fall downwelling of groundwater.

Estimates of WB residence times using salt balance techniques produced similar results for both seasons (2–3 mo), in agreement with the water balance approach for the dry season, but only half the water balance estimate obtained for the wet season. In general, salt balance models have somewhat questionable application to our relatively short salinity database for WB. Typically, these models are used for data sets obtained over long time periods and from well-mixed water bodies. For our application, the basin-averaged salinity record extends over only 7 mo. Also observations show that large horizontal salinity gradients can occur across the banks and within the basins, making the determination of the salinity of inflow and outflow waters somewhat uncertain, and thereby have a significant effect on estimates of exchange rates. Nuttle et al. (2000) used an 8 yr salinity data set from Florida Bay for 1987–1995 to calibrate a salinity box model and estimate renewal rates for the four sub-regions (east, central, south and west) of the bay that ranged from 3.6 to 7.2 mo. Residence time for the central region was estimated at 6 mo. using a mean water depth of 100 cm. Considering that the mean depth of WB is closer to 65 cm, the renewal time for this basin becomes 3.9 mo by their method. They also estimated that complete renewal of the central region waters by tidal flux would require over a year. Our estimates of seasonal water renewal times of 2–7 mo. are in reasonable agreement with Nuttle et al. (2000), however, it is important to consider that complete mixing of WB waters is not likely to occur over wind event time scales lasting only a few days. Estimates from previous studies suggest that only a fraction (0.3–0.5) of the water exchange between adjacent basins consists of new waters that had not previously resided within the basin to be flushed. Thus for WB, a 6–12 mo time scale for complete flushing of the basin is not unreasonable.

Conclusions

Local wind forcing was found to be the primary mechanism controlling water renewal within WB, the focal point of hypersalinity development in north-central Florida Bay. Eastward winds associated with cold front passages during the dry season produced a mean flow through the basin of 11 $m^3 s^{-1}$ that could renew the mean volume of WB in 2–3 mo, with inflows occurring over the broad western banks and outflows through the eastern and southern channels. During the wet season, wind events were directed primarily toward the west and southwest, causing a seasonal mean westward flow through the basin of 3 $m^3 s^{-1}$ and a basin water renewal time of 7 mo. A simple salt balance approach gave similar basin residence times, however, the occurrence of large horizontal salinity gradients indicates incomplete mixing within the basin, and the time required for complete water renewal could be up to one year. The volume of ground water input to Florida Bay had been poorly defined from previous estimates that ranged over many orders of magnitude. We used a direct water balance approach to estimate a weak ground water input to WB of 1.7 $m^3 s^{-1}$ that was necessary to balance the net loss of freshwater during the dry season. During the wet season, groundwater was estimated to downwell out of the basin at −4.7 $m^3 s^{-1}$ to account for the increase in net freshwater input.

Hypersalinity was found to develop in the central basin region in the dry season due to weak water renewal rates and the lack of freshwater inputs, especially river inputs as occurs in the northeast basin. Concerns have been raised that prolonged or intense hypersalinity in Florida Bay may have adverse local ecological effects such as sea grass die-off and algal blooms. As part of the Comprehensive Everglades Restoration Plan (CERP; Florida Forever Act, 2000), efforts are underway to restore the spatial and temporal delivery of freshwater to Florida Bay to more natural flow conditions. Our findings indicate that hypersalinity development could be regulated by redirection of a portion of the Everglades freshwater flow toward the west into the north-central basin of Florida Bay during the dry season.

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Literature Cited

Boyer, J. N., J. W. Fourqurean, and R. D. Jones. 1999. Seasonal and long-term trends in the water quality of Florida Bay. Estuaries 22: 417–430.

Csanady, G. T. 1982. Circulation in the coastal ocean. D. Reidel, Boston. 279 p.

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

Fourqurean, J. W. and M. B. Robblee. 1999. Florida Bay: a history of recent ecological changes. Estuaries 22: 345–357.

______________, R. D. Jones, and J. C. Zieman. 1993. Processes influencing water column nutrient characteristics and phosphorus limitation of phytoplankton biomass in Florida Bay: inferences from spatial distributions. Est. Coast. Shelf Sci. 36: 295–314.

Hamrick, J. M. and M. Z. Moustafa. 2003. Florida Bay hydrodynamic and salinity model analysis. Joint Conference on Science and Restoration of the Greater Everglades and Florida Bay Ecosystem, April 13–18, Abstract. 22 p.

Hittle, C. and G. Poole. 2003. Continuous hydrologic data in Florida Bay channels. Joint Conference on Science and Restoration of the Greater Everglades and Florida Bay Ecosystem, April 13–18, Abstract. 40 p.

Johns, E., W. D. Wilson, and T. N. Lee. 1999. Surface salinity variability of Florida Bay and southwest Florida coastal waters. Proc., Florida Bay and Adjacent Marine Systems Science Conference. Key Largo, November 1–5, 1999.

_______, T. N. Lee, D. Wilson, P. Ortner, R. H. Smith, and E. Williams. 2001. Salinity variability in Florida Bay from monthly high resolution surveys. Proc. Florida Bay and Adjacent Marine Systems Science Conference. Key Largo, April 23–26, 2001.

Lee, T. N. and N. P. Smith. 2002. Volume transport variability through the Florida Keys tidal channels. J. Cont. Shelf Res. 22: 1361–1377.

________ and E. Williams. 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.

________, _____________, D. Wilson, E. Johns, and N. Smith. 2002. Transport processes linking south Florida coastal ecosystems. Pages 309–342 *in* J. W. and K. G. Porter, eds. The Everglades, Florida Bay and Coral Reefs of the Florida Keys: an ecosystem sourcebook, CRC Press, Boca Raton.

Light, S. S. and J. W. Dineen. 1994. Water control in the Everglades: a historical perspective. Pages 47–84 *in* S. M. Davis and J. C. Ogden, eds. Everglades: the ecosystem and its restoration. St. Lucie Press, Delray Beach.

Melo, N., D. S. Bitterman, R. H. Smith, D. Wilson, and T. N. Lee. 2003. Florida Bay shallow water surface drifter. Joint Conference on Science and Restoration of the Greater Everglades and Florida Bay Ecosystem. April 13–18, Abstract. 56 p.

Nance, J. M. 1994. A biological review of the Tortugas pink shrimp fishery through December 1993. Galveston Laboratory, Southeast Fisheries Science Center, National Marine Fisheries Service, Galveston.

Nuttle, W. K., P. M. Price, and P. K. Swart. 2003. Variation of evaporation from Florida Bay. Joint Conference on Science and Restoration of the Greater Everglades and Florida Bay Ecosystem. April 13–18, Abstract. 61–63 p.

___________, J. Fourqurean, B. Cosby, J. C. Zieman, and M. B. Robblee. 2000. The influence of net freshwater supply on salinity in Florida Bay. Water Resour. Res. 36: 1805–1822.

Orlando, S. P., Jr., M. B. Robblee, and C. J. Klein. 1998. Salinity characteristics of Florida Bay: a review of the archived data set (1955–1995). Silver Springs: NOAA, Office of Ocean resources Conservation and Assessment, 32 p.

Press, W. H., S. A. Teucholsky, W. T. Vetterling, and B. P. Flannery. 1992. Numerical recipes in fortran: the art of scientific computing. 2nd ed. Cambridge Univ. Press.

Robblee, M. B., T. R. Barber, P. R. Carlson, M. J. Durako, J. W. Fourqurean, L. K. Muehlstein, D. Porter, L. A. Yabro, R. T. Zieman, and J. C. Zieman. 1991. Mass mortality of the tropical seagrass *Thalassia testudinum* in Florida Bay. Mar. Ecol. Prog. Ser. 71: 297–299.

Smith, D. 1999. Everglades National Park Marine Monitoring Network 1998 Data Summary. Everglades National Park, South Florida Natural Resources Center, Homestead. Data Report, 100 p.

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

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

USGS. 2005. U.S Geological Survey, South Florida Ecosystem Program: Place-Based Studies, Freshwater Flows into Northeastern Florida Bay. Estuarine Creek Data Set. Available from: http://sofia.er.usgs.gov/projects/freshwtr_flow/

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

_________, J. van de Kreeke, N. Krishnan, and D. Smith. 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.

Zieman, J. C., J. W. Fourqurean, M. B. Robblee, M. Durako, P. Carlson, L. Yabro, and G. Powell. 1988. A catastrophic die-off of seagrasses in Florida Bay and Everglades National Park: extent, effect, and potential causes. Eos 69: 1111.

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