National Park Service
U.S. Department of the Interior

South Florida Natural Resources Center
Everglades National Park

STATUS AND TRENDS REPORT

SFNRC Technical Series
2012:1

Salinity and Hydrology of Florida Bay

Status and Trends 1990–2009

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South Florida Natural Resources Center
Everglades National Park
Homestead, Florida

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Cover photograph shows aerial view of Eagle Key in Florida Bay, Everglades National Park.
Photo by William Perry.

Salinity and Hydrology of Florida Bay: Status and Trends 1990–2009

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EXECUTIVE SUMMARY

The National Park Service began long-term monitoring in Florida Bay in 1988 and had expanded the network to its current size of 17 stations by 1995. This report analyzes hydrologic and salinity data from the Everglades National Park (ENP) marine monitoring program, ENP Taylor Slough flow monitoring effort, U.S. Geological Survey (USGS) coastal creek discharge monitoring effort, and information from several individual studies on evaporation rates. The report summarizes conditions in Florida Bay during the 2009 calendar year, discussing trends in those conditions for the available period of record for data collection efforts, focusing on 1990–2009. The report's focus is on factors influencing salinity, recognized as the primary driver of ecological conditions in the bay. Data from Florida Bay have been grouped into zones, with the western zone being least directly influenced by freshwater outflow from the coast, and the eastern zone most closely tied to freshwater discharge. Between these, the central zone contains the most isolated basins in the bay and the southern zone represents stations closer to the Intracoastal Waterway and the Florida Keys.

The year 2009 was marked by a drier-than-average wet season, followed by two unseasonably large rain events leading into the 2010 dry season. Rainfall distribution reflects regional and convective wind and rain patterns, with more precipitation along the shoreline than in the rest of the bay. There were no tropical storms, and therefore no tropical-storm-related impacts on precipitation, in Florida Bay in 2009. The wet season began slightly late in 2009 and had below average rainfall. The delayed onset and low rainfall rates led to low flow in Taylor Slough and a related high salinity event in the Taylor River, with the 30-day average salinity exceeding 30 practical salinity units (PSU) from April 19 through June 15. To the south, in Florida Bay, an extended hypersaline event was observed at Whipray Basin, where salinity was above 40 PSU for 193 days. The highest salinity value observed was 62.7 PSU measured at Garfield Bight on May 1, 2009. In November and December of 2009, we observed above average dry-season rainfall in association with the positive phase of the El Niño Southern Oscillation. In particular, two large rain events together produced more than 7 inches of rainfall directly on Florida Bay, bringing the annual bay-wide total rainfall to 48.5 inches. Salinity decreased during these rain events late in the year; however, because salinity was well above average prior to the events, these events weren't large enough to reduce salinity to or below the mean for November or December in the period of record. Evaporation for 2009 was calculated by proxy to be 43.8 inches, which was 3.7 inches less than the bay-wide total rainfall.

Water temperatures in Florida Bay showed a cooler-than-average winter with a warmer-than-average summer, with average monthly temperatures as low as 19 °C in February and climbing above 31 °C in July. These values are within the lower and upper 10th percentile of the period of record respectively. Temperature was more variable in the shallow basins along the Florida coast than in the deeper basins. The coldest individual temperature reading was 7 °C at Buoy Key on February 5. Temperature, salinity, and stage data were used together to determine that lowest temperatures occurred during the outgoing tide when cold surface waters from the upstream marsh were delivered into the coastal zone. On February 5, the largest of these tidally driven events caused a change in temperature of slightly greater than 1 °C per hour. Temperature change, in addition to salinity, has an effect on the dissolved oxygen solubility limit, with oxygen solubility increasing as temperature decreases. The lowest solubility limit value of 5.3 mg/L was observed on May 12 at Buoy Key, when both salinity and water temperature were approaching their peak values. No significant fish or seagrass die-off events were associated with the high-temperature-related low-oxygen solubility limit event in May of 2009. The oxygen concentration and saturation state for surface waters were not directly measured.

Low tide as viewed from Flamingo, on the northern coast of Florida Bay. Located at the tip of peninsular Florida, Flamingo is accessible by car at the end of the main park road, or by boat. Myriad species of wading birds, water birds, and other wildlife live all or part of the year on the ecologically productive mudflats of the Florida Bay estuary.

Photo by William Perry.

Two significant and possibly related findings with respect to salinity in Florida Bay for 2000–2009 included: (1) a trend toward increasing salinity in the eastern and central zones and (2) recurrent high salinity events in the Taylor River. Salinity in these estuarine zones is, on average, rising and approaching marine conditions for most of the year. Sections of the bay experience hypersalinity, above 40 PSU, for weeks (eastern zone) to several months (central zone) of the year. The cause of the 10-year trend of increasing salinity reflects an imbalance in quantities and a change in the timing of freshwater inflows and freshwater losses. The highest salinity events and highest rate of salinity increase were observed during the dry season.

A freshwater budget was developed to quantify the relative impact of different freshwater sources on salinity. In this analysis, the deviation between the predicted and observed salinity values was more pronounced during the dry season when evaporation, the term in the freshwater budget with the largest uncertainty, is the dominant factor. This suggests that a more accurate measurement of evaporation in the bay is needed to understand the water budget. Increasing the frequency or extent of evaporation data collection would have a positive impact on our understanding of the freshwater budget. Additionally, improved hydrodynamic models that accurately depict the exchange between basins may clarify the impact of freshwater components on salinity. Combining the freshwater budget and salinity data with observations of sea-level rise, approximately 1 inch in the last decade, will help in predicting future salinity conditions in Florida Bay.

While freshwater discharge from the marsh affects salinity in Florida Bay, it also acts as a barrier to salt-water intrusion into the marsh. One location that is closely monitored for salt-water intrusion is station TR in the Taylor River, where a State of Florida Minimum Flows and Levels (MFL) Rule, which is intended to prevent significant ecological harm to the Florida Bay region, specifies a maximum 30-day average salinity threshold of 30 PSU at TR. In the past decade, four high salinity events in two back-to-back time periods occurred at this location, first in 2004–2005 and again in 2008–2009. If the trend toward higher dry-season salinity values in Florida Bay continues, Taylor River will likely experience violations of the salinity guidelines in the MFL Rule. Further, if the observed trends toward higher salinity and higher sea level continue, and additional freshwater is not provided to Taylor Slough, these events may become more common. Management will continue to monitor conditions, evaluating the effectiveness of current freshwater flow to maintain an appropriate salinity regime.

Rankin Bight in Florida Bay.
Photo by Lori Oberhofer, ENP.

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FOREWORD

This report, "Salinity and Hydrology of Florida Bay: Status and Trends 1990–2009," provides a summary and analysis of data collected by National Park Service and U.S. Geological Survey staff. The technical analysis in this paper supports National Park Service efforts toward understanding the physical coastal environment of Everglades National Park. This knowledge enhances the ability of the Service to meet its responsibility for preserving our nation's natural and cultural resources while engaging in ecosystem restoration efforts in south Florida. The results presented herein establish the spatial and temporal variability in the coastal environment, providing guidelines for detecting change and assessing effectiveness of resource management projects in meeting the park's long-term objectives.

Variability and trends in Florida Bay conditions during the 1990–2009 time period are described in the report and compared to 2009 conditions in particular. This report focuses on the factors that influence salinity, which is recognized as the primary driver of the ecological conditions in the bay, particularly the distribution and abundance of estuarine species. Much of the bay currently experiences hypersaline events (salinities greater than 40 practical salinity units), and reducing the frequency, severity, and spatial extent of these hypersaline events is a key goal in Everglades restoration. Salinity is driven by the balance of freshwater inputs, which is dominated by the local rainfall and, to a lesser extent, inflows from upstream sources. The net freshwater flux in the bay indicates that increasing dry-season inflows would provide the greatest overall benefit, particularly by reducing salinity fluctuations in the nearshore areas and central Florida Bay. The analysis also shows that sea level in Florida Bay is rising at a rate of approximately 1 inch (25 mm) per decade, similar to the rate observed at the sea-level monitoring station in Key West, a reminder of the relationship of conditions in the park to regional trends. This finding, together with the observation of considerable year-to-year variability in salinity, makes it apparent that the hydrologic regime of the bay is complex and doesn't present a simple target for comparison with Everglades restoration goals. Rather, this study highlights the realities of a dynamic system. A concerted effort is needed to continue to clarify the effects of precipitation, discharge, and mixing on salinity in the semi-isolated basins of Florida Bay. Ultimately, the ability to meet nearshore salinity targets will depend on both the proper selection of upstream restoration projects and a deep understanding of this dynamic coastal system.

It has been our pleasure to work with our federal, state, and non-profit partners in the collection of data for this program. The National Park Service looks forward to continued cooperation as we work to maintain and improve conditions in Florida Bay, a valuable natural area of great importance to the region.

Robert Johnson
Director
South Florida Natural Resources Center
Everglades National Park

December 2012

Eastern Joe Bay and Trout Cove in the northeastern part of Florida Bay.
Photo by William Perry.

"Here are no lofty peaks seeking the sky, no mighty glaciers or rushing streams wearing away the uplifted land. Here is land, tranquil in its quiet beauty, serving not as the source of water, but as the last receiver of it. To its natural abundance we owe the spectacular plant and animal life that distinguishes this place from all others in our country."

President Harry S. Truman, address at the Dedication of Everglades National Park, December 6, 1947

INTRODUCTION

Florida Bay is a large (approximately 2,200 km^2), shallow lagoon bounded to the north by the Florida peninsula and to the south and east by the Florida Keys. Though connected to the Gulf of Mexico to the west, the gulf and the bay have limited exchange of water due to the presence of a series of shallow banks, typically covered with and stabilized by seagrass communities. These banks separate the bay into basins, each with its own physical characteristics. These basins provide unique habitat for many plants, invertebrates, fishes, birds, mammals, and reptiles, including several threatened or endangered species including the Florida manatee (*Trichechus manatus latirostris*) and species of special concern such as the roseate spoonbill (*Platalea ajaja)*. Approximately 1,625 km^2 of Florida Bay are located within Everglades National Park and protected by the National Park Service, while the remainder lies within the Florida Keys National Marine Sanctuary and falls under the jurisdiction of the National Oceanic and Atmospheric Administration. In order to preserve and protect Florida Bay, managers at Everglades National Park needed to improve their understanding of this system. To that end, hydrologic monitoring stations were installed in the bay and in the upstream freshwater marshes of the park. Data from this network, including conductivity (used to calculate salinity), water temperature, water level, and rainfall measurements, are transferred in near real-time to a MySQL database system and are available via an interactive web server (SFNRC DataForEVER Dataset, 2010). This report, based on the MySQL dataset and supplemented with publicly available data from the South Florida Water Management District's DBHydro database (2010, available at www.sfwmd.gov), reviews the physical conditions in Florida Bay for 2009 and places those conditions in the context of the period of record for the Florida Bay dataset, roughly 1990 through 2009.

In the previous century, the freshwater system of south Florida was drastically altered from its natural state to that of a highly managed system. The majority of freshwater that historically flowed to the south was diverted to the ocean by a network of about 2,400 km of canals (Davis and Ogden, 1994). During the late 1980s to early 1990s, the Florida Bay ecosystem exhibited many signs of stress including large-scale seagrass die-off events (Robblee et al., 1991). The system historically described as rich with game fish swimming in clear waters has trended toward more turbid and opaque waters with reduced productivity. Concomitant with the seagrass die-offs, a massive and prolonged algal bloom and associated regional sponge die-off event led to a decline in the Caribbean spiny lobster (*Panulirus argus*) (Butler IV et al., 1995) and game fish populations (Fourqurean and Robblee, 1999). Events such as these appear to be sporadic, episodic, and ongoing in the south Florida region (Gunter et al., 1948).

Many ecological issues affecting the bay have been investigated and numerous associated scientific papers published. In some cases, our understanding of events in the bay appears to be essentially complete. For example, a mass fish mortality event near Buoy Key in 1991 was determined to be related to low oxygen levels following a large, seasonal seagrass die-off (Robblee et al., 1991). In other cases, proposed explanations for changes to the system have proven more contentious and studies are ongoing. Numerous Florida Bay science workshops have been held and several outstanding papers providing summaries of a variety of issues affecting Florida Bay are now available. The reader is directed to an excellent review by Fourqurean and Robblee (1999) for historic context, and to a 2009 special issue of *Ecological Indicators* for a more recent overview of scientific studies in Florida Bay. In 1994, researchers concluded "... that productivity of Florida Bay is declining under current management practices" (Davis and Ogden, 1994). Recent assessments are more positive, citing the bay's resiliency in recovering from mass seagrass and fish mortality events as cause for optimism (Fourqurean, pers. comm.)

Everglades National Park staff has studied conditions within Florida Bay with the knowledge that this coastal region, open to the ocean on its western boundary, is also a managed system with water quality affected by overland flows to the bay. The net outflow along the southern coast of Florida into Florida Bay is a combination of surface runoff due to rainfall within the park and controlled releases to the park through structures in the water management system. There is also the potential for groundwater flow, which is influenced by water levels in the park and in the neighboring canals of the South Dade Conveyance System. The primary features of the system are the L–31W and C–111 canals that border Everglades National Park (Fig. 1). These canals and related structures function to alter the spatial and temporal distribution of freshwater input to the park. The two main regions along the mainland that act as flow-ways for surface freshwater, and therefore influence salinity in Florida Bay, are Taylor Slough and the eastern panhandle. Operation of structures in or connected to the L–31W canal influences levels in the canal and the quantity of flow through Taylor Slough. The operation of the S–18C structure, a control feature in the C–111 canal, affects the amount of water that is permitted into the southern terminus of the C–111 canal. Water levels in the canals are monitored and adjusted by the South Florida Water Management District (SFWMD) to supply water and provide flood protection to the adjacent communities, maintain favorable conditions for farming in neighboring agricultural lands, and to benefit the park while meeting these regional requirements. As such, the operational guidelines for the structures in the canals reflect the compromise between competing needs in the region.

The purpose of the analysis presented in this report is (1) to describe the status of the physical conditions in Florida Bay during 2009 including precipitation, evaporation, water temperature, surface-water inflows, and salinity, and (2) to discuss trends in those conditions primarily from 2000 through 2009 but extending the analysis to longer-term datasets where appropriate and available. Analyses for the 2009 status component are based on the calendar year with emphasis on the monthly sequence of events that define conditions through

2009. Analyses for the trends component use a continuous time-series for the period of interest, with the dry season for a given year extending from November of the previous year through May and the wet season defined as June through October of that year. For example, the 2009 dry season extends from November 2008 through May 2009 while the wet season extends from June through October, 2009. The study area includes Florida Bay, the coastal creeks connecting to Florida Bay, Taylor Slough, and the eastern panhandle region including the C–111 canal and associated structures (Fig. 1). Evaporation data were unavailable for Florida Bay for most of the period of interest for this study so a proxy was developed for evaporation based on measurements made at a marsh station within Everglades National Park and a study of evaporation within Florida Bay. The report's emphasis is on factors affecting salinity in the bay.

Regional Extent and Monitoring Locations

Florida Bay is composed of a series of shallow basins, each partially isolated from its neighbors by shallow seagrass-stabilized banks. For the purpose of this report, the basins are grouped into the following functional zones (Fig. 1). A table describing the station locations and monitoring parameters is provided in the appendix, located at the back of the report.

- **Western Zone**—a region primarily influenced by its open western boundary where it exchanges water with the Gulf of Mexico. This region has three monitoring stations, all established in 1993, located at Murray Key (MK), Johnson Key (JK), and on the northern side of Little Rabbit Key (LR), and includes the Twin Keys, Rabbit Key, and Johnson Key basins. Due to its open western boundary, conditions in this region are generally more closely tied to regional marine conditions for salinity and are influenced by tides to a greater degree than the remainder of the bay.
- **Central Zone**—a region along the central, northern shore of Florida Bay typified by the most shallow and restrictive banks and most isolated basins. This region has five monitoring stations which are, proceeding west to east, at Buoy Key (BK, Est. 1993), which is south of Snake Bight; at Garfield Bight (GB, Est. 1996), which is northeast of Snake Bight; at Terrapin Bay (TB, Est. 1991), which is farther east along the coast; at Whipray Basin (WB, Est. 1989), located in the center of the zone and surrounded by shallow (<0.5m) banks; and at Little Madeira (LM, Est. 1988), outside the mouth of Little Madeira Bay. Station LM is included in the Central Zone in this report because the station is partially separated from coastal freshwater flow due to its location, just outside of Little Madeira Bay (Fig. 1). The central zone is partially isolated from the coastal ocean, exhibits a relatively small tidal range and associated exchange, and has a history of high salinity events. Also, this region is prone to annual phytoplankton blooms that are likely driven by a combination of nutrient input, high temperature, and high light conditions within these shallow seasonally hypersaline basins.
- **Eastern Zone**—a region along the northeastern boundary of Florida Bay where salinity is affected by surface-water runoff from the eastern panhandle region and overbank flows from the canal system along the south side of C–111, south of S–18C. This region also borders the series of islands where the Overseas Highway (U.S. 1) connects the Florida Keys to the mainland. There are six stations in this region including a station in Joe Bay (JB, Est. 1993), a station in Trout Cove (TC, Est. 1988) south of Joe Bay, a station in Long Sound (LS, Est. 1988), a station on the western side of Duck Key (DK, Est. 1988), a station in Little Blackwater Sound (LB, Est. 1991), and a station in Blackwater Sound (BS, Est. 1991). During 2005–2007, this region experienced an extensive and long-lived phytoplankton bloom that was suspected to have been triggered by a combination of heavy rainfall events associated with hurricanes and the remobilization of nutrients from soils disturbed during an upgrade of the Overseas Highway.
- **Southern Zone**—a region along the southern boundary of the park bordering the Intracoastal Waterway. This region contains three stations, including a station at Peterson Key (PK, Est. 1989), a station near Bob Allen Keys (BA, Est. 1993), and a station near Butternut Key (BN, Est. 1990).
- **Boundary Stations**—stations that are not in Florida Bay but provide valuable information about the neighboring ecosystems. In this report, data from a station in the upper Taylor River near the interface of freshwater and saline marshes (TR, Est. 1988) were used as a measure of salt-water intrusion to the neighboring marsh. Freshwater discharge along the northern boundary of Florida Bay is measured at the mouth of several creeks flowing from Taylor Slough (TRE, Est. 1995, ECR, Est. 2006, and MUD, Est. 1995), at a station located at the connection between Joe Bay and Trout Cove (TROUT, Est. 1996), at a station in Stillwater Creek (SWC, Est. 1999) leading to western Long Sound, and at stations located in Highway Creek East (HCE, Est. 2001) and Highway Creek West (HCW, Est. 1996) leading to eastern Long Sound.

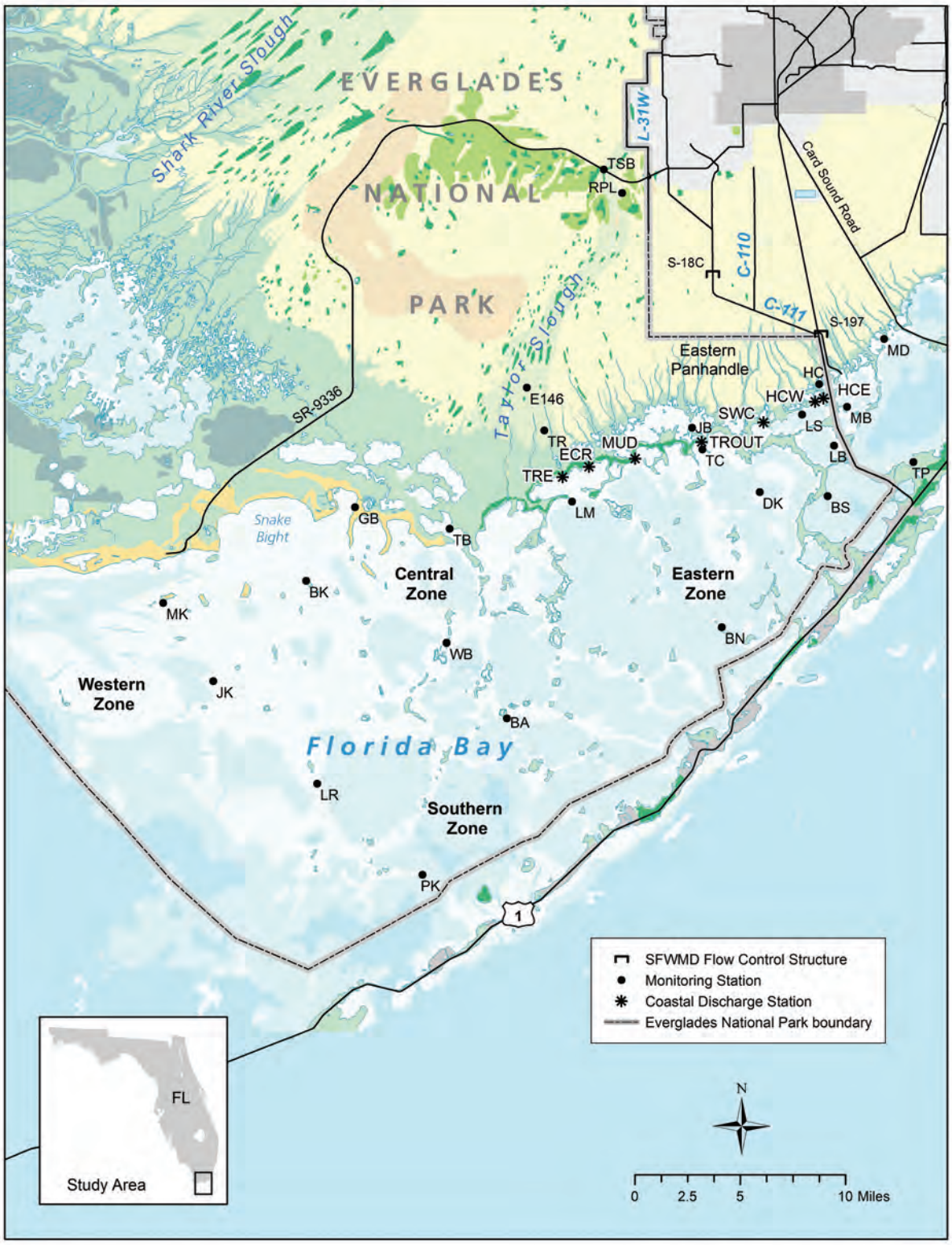

Figure 1. Location of monitoring stations, freshwater canals and structures, and ecological zones in the Florida Bay study area.

FLORIDA BAY STATUS: 2009

Precipitation

Precipitation affects salinity within Florida Bay either directly, by altering the balance between precipitation and evaporation, or indirectly, due to precipitation on the local watershed and its subsequent delivery to the bay via sheetflow or streamflow. Precipitation is inherently variable in both time and space. This section reviews precipitation within Florida Bay and upstream in Taylor Slough. During 2009, precipitation data were collected at an extensive set of monitoring stations throughout Florida Bay and in Taylor Slough (Fig. 2). No extreme tropical storms or hurricanes that could have drastically affected precipitation patterns or amounts occurred in Florida Bay during 2009. Annual precipitation for south Florida, the region extending from Lake Okeechobee to the southern tip of the Florida mainland, in 2009 was 48.49 inches or 6.7% below the annual average of 52.00 inches for 1976–2001. In Florida Bay, the basin-wide total precipitation was 40.66 inches, which is 16% lower than the 2009 south Florida precipitation. Florida Bay had less precipitation than south Florida, and south Florida was experiencing lower-than-average precipitation for the year. Florida Bay's regional distribution of precipitation is shown in Figure 2, with greater amounts of precipitation along the coast and in the neighboring freshwater slough than in the southern or western portions of the bay. Florida Bay is a seasonally hypersaline estuary, with the distribution of salinity values related to the distribution of precipitation and the subsequent mixing of water between basins (Kelble et al., 2007). The spatial distribution of precipitation, with higher precipitation along the coast, is consistent from year to year, and the data indicate that 2009 was an average year in this respect.

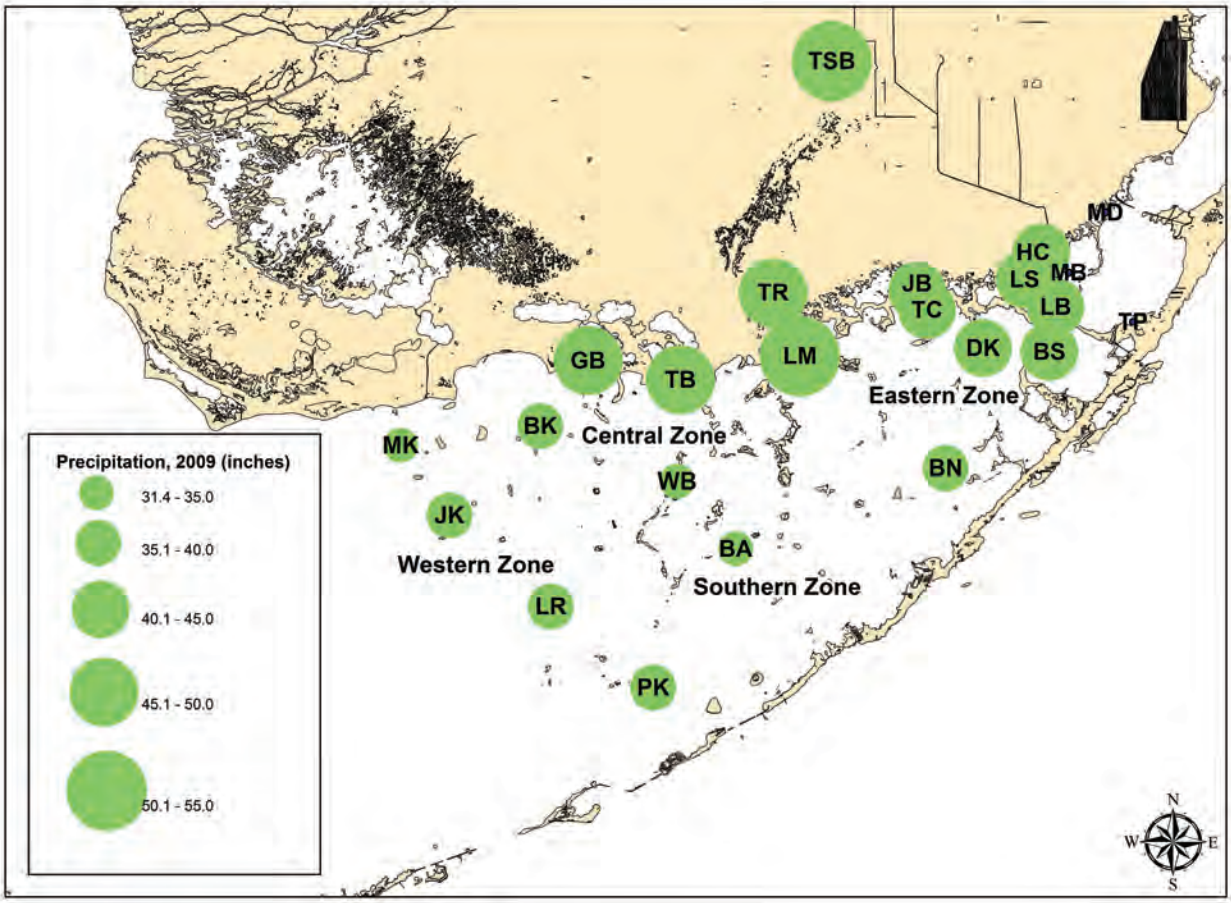

Figure 2. Precipitation at study area monitoring stations in 2009.

The quantity of precipitation is influenced by the El Niño Southern Oscillation (ENSO) through its impact on sea surface temperature, evaporation rates, and global circulation patterns (McPhaden et al., 2006, and references therein). Due to its significance in global hydrologic cycles and heat transfer budgets, considerable effort has been put into tracking the ENSO through a standardized long-term Oceanic Niño Index (ONI) (Smith et al., 2008). For this report, we are using NOAA's Extended Reconstructed Sea Surface Temperature (ERSST) version 3b dataset (Oceanic El Niño Index, 2011). ENSO-related variation in the ONI has a complex relationship with precipitation in Florida, ranging from no impact to a slight reduction of precipitation during the wet season to an increase in precipitation during the dry season (Hagemeyer, 2006). Higher-than-average dry-season precipitation can be significant for coastal areas as it causes a reduction in salinity and a reduction in residence times in coastal basins due to increased flushing (Childers et al., 2006). With respect to ENSO, 2009 was a transitional year, moving from negative to positive values for the ONI. The transition from a neutral or slightly negative (La Niña) phase to a positive phase (El Niño) occurred in July. This may have contributed to the lower-than-average precipitation in 2009 from January through the end of September. This lower-than-average precipitation was then partially offset, in terms of the annual average, by two large rainfall events, totaling 7.74 inches in November and December. Coinciding with these events was a shift of the ENSO signal to the positive phase. As El Niño impacts on rainfall are cyclical and of variable duration (Hagemeyer, 2006), it may be valuable to continue monitoring its phase in order to better understand the potential for lower- or higher-than-average precipitation during upcoming dry seasons[1].

Within Florida Bay and in the coastal basins, 18 stations measured rainfall at hourly resolution through 2009 as part of a period of record of as much as 18 years (Table 1). The lowest annual rainfall for the western region was 34.40 inches, observed at the Murray Key station (MK), while the lowest annual rainfall for the southern region was 33.70 inches, observed at the Bob Allen Keys station (BA). In contrast, the bay-wide maximum rainfall of 50.48 inches was observed at the Little Madeira Bay (LM) station, located in the central region of the bay. These spatial trends are visible in Figure 2. The spatially weighted bay-wide average total annual rainfall was calculated using the ArcGIS spatial analysis toolbox (ArcGIS v. 10, ESRI, Inc.). For 2009, annual precipitation was 40.66 inches, which ranked as the sixth highest in the period of record and yet was not statistically different from the long-term average of 39.0 ± 7.4 inches observed since 1992. The time series of cumulative rainfall in the bay is shown in Figure 3 by zone, with precipitation in May and June accounting for 14.96 inches and precipitation in September accounting for an additional 6.58 inches. The total rainfall in these three months was 53% of the annual rainfall. In contrast, only 1.90 inches of rain fell across the bay during the first four months of 2009.

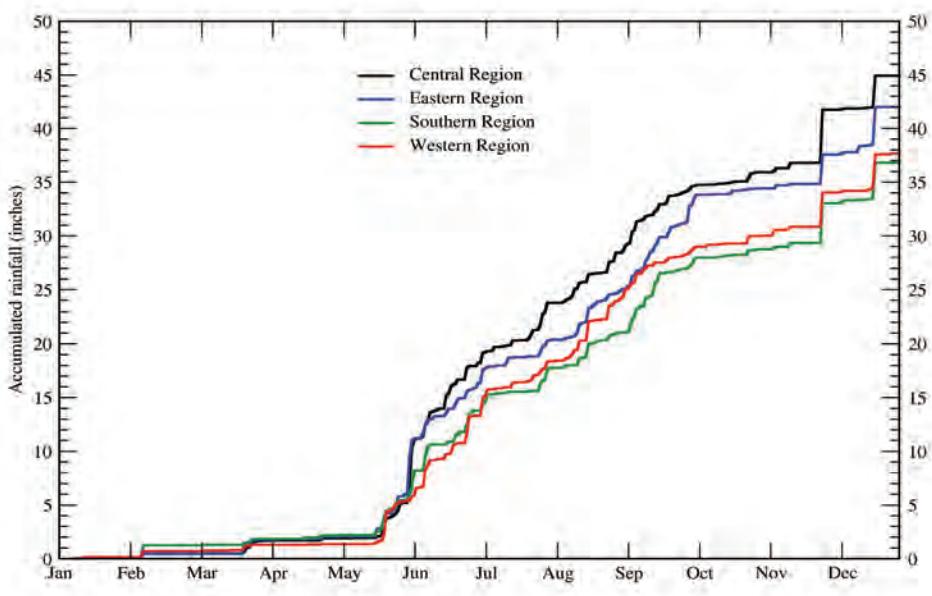

Figure 3. Cumulative precipitation by zone for Florida Bay during 2009.

1 For ongoing monitoring of ENSO status and forecasts of its impact on rainfall in Florida, the reader is referred to http://www.cpc.ncep.noaa.gov

Local differences in the quantity and timing of rainfall are evident between stations in Florida Bay. In 2009, a series of fairly uniform but small rainfall events occurred until late-May when the wet season began. During May 29–30, more than 5 inches of rain fell on Florida Bay with a trend toward slightly greater amounts of rainfall in the more isolated central and eastern regions of the bay relative to the southern or western regions (Table 1). The location of rainfall within Florida Bay is significant because of differences in residence times between basins across the bay. The semi-isolated central and eastern basins have longer residence times than the more open southern or western regions (Wang et al., 1994). A basin's change in salinity per unit rainfall is affected by the basin's volume and the residence time, which in turn is a function of mixing between neighboring basins. For instance, in 2009, a 2-day, approximately 5-inch rain event in May caused the salinity within Whipray Basin, a highly isolated basin in the central zone, to decrease from 44.4 practical salinity units (PSU) on May 28 to 41.0 PSU on May 31 and then increase back to 44.3 PSU by June 10, 13 days later. This roughly 2-week recovery time for salinity after a rain event may indicate a residence time much shorter than a published estimate for this area, in the range of 3 to 6 months (Lee et. al., 2006). The longer residence times derived in Lee's work (2006) are based on stage, flow measurements, and several assumptions including that the region is uniformly mixed. In contrast, the rapid increase in salinity observed in this study is based on sensor data at a single location on a shallow bank and therefore could be influenced by its location in a number of ways including, but not limited to: (1) limited exchange and high evaporation in the shallow grass beds surrounding the station causing salinity to increase more rapidly on the bank than on average across the basin, (2) increased mixing with high salinity waters on the shallow banks being brought into the region with tides, or (3) the sensor detecting higher salinity water due to being located near the bottom of a potentially stratified water column.

In contrast to the conditions in Whipray Basin, other regions along the western edge of Florida Bay are less isolated and exhibit more rapid returns to previous salinity levels following rain-induced salinity declines. For instance, a 2-inch rain event on June 30 at Murray Key, a western region station with strong tidal exchange, caused a reduction in salinity from 38.6 PSU to 36.8 PSU that lasted only 1 day before beginning to increase again and only 4 days before returning to the longer-term salinity trend line. Including the caveat that the observations are certainly influenced by site-specific features such as sensor depth and the amount of water movement through the sensor location, these observations still show that salinity reductions due to rain in the central region are maintained for a longer period of time than in other regions of the bay. A detailed study on mixing between basins and within basins would likely clarify the relationship between residence time and the observed duration of salinity variation due to rain in Florida Bay.

Table 1. Monthly precipitation data by station, 2009.

	Western			Central				
	JK	**LR**	**MK**	**BK**	**GB**	**TB**	**WB**	**LM**
January	0.21	0.19	0.12	0.12	0.35	0.12	0.07	0.04
February	0.31	0.93	0.37	0.35	0.31	0.30	0.59	0.24
March	0.85	0.64	0.31	0.48	1.62	1.84	0.01	1.24
April	0.03	0.01	0.08	0.25	0.28	0.13	N/A	0.23
May	3.42	4.93	5.09	8.39	4.08	10.96	6.01	13.13
June	12.80	6.33	8.42	9.18	14.11	7.99	4.37	4.83
July	3.78	3.69	2.60	3.34	7.39	3.71	2.64	6.12
August	6.76	5.16	7.98	5.14	4.94	6.65	4.89	4.56
Septeber	4.43	4.52	2.56	4.46	10.27	4.11	2.21	7.00
October	1.02	1.72	0.81	0.36	0.62	0.43	1.31	3.77
November	3.00	5.71	3.29	4.07	0.04	6.78	6.63	5.93
December	3.18	4.89	2.77	3.75	3.12	2.31	3.16	3.39
Total	39.79	38.72	34.40	39.89	47.13	45.33	31.89	50.48

Evaporation

Florida Bay is a seasonally hypersaline estuary, where evaporative losses exceed the combined influx of freshwater from all sources for at least a portion of the year. Determining the balance between precipitation and evaporation is critical to determining the overall water budget, an accounting of all additions of water and losses of water for the bay. Precipitation was measured at each station in the bay, and estimates were used to determine evaporation. In summer, enhanced convection causes increased precipitation in the Everglades and along its shoreline. Feedback cycles, such as the increase in cloud cover, reduce the temperature differential and associated intensity of convective processes resulting in decreased evaporation rates. The result is a complex system of highly variable evaporation in the freshwater to marine transition zone.

The availability of evaporation data is limited in Florida Bay. Price et al. (2007) sought to address this issue by determining evaporation in the bay during a 2001–2002 study. In that effort, two stations were outfitted to determine evaporation via either (1) a radiative balance approach based on radiative flux measurements combined with the rate of change in water temperature and the difference between water and air temperature or, (2) a vapor flux method that used wind speed, water and air temperatures, and relative humidity to determine mass-transfer as a function of turbulence. The study locations were Butternut Key and Little Rabbit. The result of their study was an evaporation estimate of 64.2 ± 5.9 inches for the study period. Price et al. (2007) went on to extend the time period of their study, using temperature and solar radiation data from stations at Flamingo and Royal Palm, in the park, and at Tavernier in the Florida Keys to develop a time series for 1970–2002. The resultant time series of annual estimated evaporation had a mean of 65.3 inches and range of 58.2 to 71.2 inches evaporation per year. This value was above the model-based average evaporation of 43.3 inches established by Nuttle et al. (2000), but in close agreement with an alternate observation-based calculation of 64.2 inches (Smith, 2000). The Price et al. (2007) data were then used to estimate baywide evaporation for more recent years in the study period. To produce these estimates, a ratio was determined between the observed evaporation at a marsh station located at Forty Mile Bend (station FMB) and the evaporation estimates for Florida Bay developed by Price et al. (2007) for 1970–2002. This ratio was then applied to evaporation data from station FMB for 2009 to create a baywide estimate of evaporation of 43.8 inches. This is greater than the baywide rainfall of 40.66 inches, which is in agreement with the general trend of annual evaporation exceeding annual precipitation in Florida Bay, a seasonally hypersaline lagoon (Kelble, et al., 2007). The balance between evaporation and precipitation is discussed in detail the "Freshwater Budget" section of this report.

Table 1. Monthly precipitation data by station, 2009—Continued.

		Eastern							Southern		
	JB	TC	DK	HC	LS	LB	BS	PK	BA	BN	Average
Jan.	0.05	0.09	0.07	0.29	0.25	0.31	0.10	0.11	0.17	0.12	0.15
Feb.	0.00	0.24	0.33	0.44	0.31	0.42	0.32	2.04	0.92	0.36	0.49
March	0.59	0.53	0.62	1.86	1.98	2.16	1.62	0.77	0.30	0.75	1.01
April	0.32	0.13	0.36	0.20	0.35	0.23	0.58	0.57	0.24	0.28	0.25
May	13.73	12.05	7.17	7.38	7.52	8.37	7.30	5.56	4.56	7.82	7.64
June	3.31	6.62	6.14	4.92	6.37	8.41	9.11	7.09	4.69	7.07	7.32
July	3.51	3.24	2.98	3.39	3.38	2.46	0.73	2.90	3.17	3.81	3.49
August	3.28	3.52	4.34	5.27	6.32	4.79	4.97	4.90	2.17	2.75	4.91
Sept.	7.32	7.80	12.70	8.85	6.75	7.20	7.95	7.16	4.89	8.25	6.58
Oct.	0.56	0.98	1.41	0.94	0.75	1.42	0.71	0.71	1.41	0.72	1.09
Nov.	4.70	3.64	3.04	2.91	2.85	2.53	2.42	4.90	6.24	1.70	3.91
Dec.	3.48	4.00	4.04	4.99	4.71	4.97	4.81	2.42	4.94	4.02	3.83
Total	40.85	42.84	43.20	41.44	41.54	43.27	40.62	39.13	33.70	37.65	40.66

Water Temperature

Water temperature was determined in the shade, approximately 1 foot off the bottom, at all stations in Florida Bay. Monthly average temperature data for each zone in Florida Bay (Figs. 4 and 5) are superimposed on box and whisker plots showing the statistical distribution of temperature data for each month in the period of record. For 2009, the water temperature was exceptionally low in February on average, with the coldest average monthly values occurring in the western basin at 19.26 °C followed by the southern basin at 19.77 °C. In both basins, the average February temperatures observed for 2009 were below the 10th percentile for the period of record. In south Florida, low water temperature events are often driven by cold fronts passing into the region. Changes in air temperature, wind speed, and wind direction can be good indicators of these events passing through the region.

Several short-duration cooling events along the coast in Florida Bay at the beginning of 2009 had relatively rapid rates of change and lower low temperatures at shallow station locations than what was observed at deeper locations farther from the coast. The 6.97 °C bay-wide low temperature of 2009 was reported at 8:00 a.m. on February 5 at Buoy Key in the central zone. This cold weather event was more pronounced inland with a minimum air temperature of 1.1 °C observed at the Royal Palm station in Taylor Slough that same night. The low water temperature event at Buoy Key is likely a combination of direct cooling at the station combined with transfer of colder water from neighboring areas, including shallow banks or from Taylor Slough, to the station during the outgoing tide. At Buoy Key, for example, as low tide approached on February 5, salinity dropped from 33 to 30 PSU and the temperature dropped from 21.95 to 6.97 °C. The corresponding drop in salinity with a drop in temperature is suggestive of water from Garfield Bight, or ultimately Taylor Slough, as a source for the cold, lower salinity water. Salinity data from other neighboring stations showed higher salinity waters and precipitation data show no precipitation in the 48 hours before the event. After the event, salinity increased back to 33.5 PSU and temperature increased to 16.40 °C on the incoming tide. This cycle continued with salinity falling back to 31.0 PSU and a water temperature falling to 7.48 °C at the bottom of the next outgoing tide. Both salinity and water temperature reach their lowest value for the tidal cycle approximately 2 hours after the lowest stage is observed on the outgoing tide. Both the decrease in temperature on the outgoing tide and the increase in temperature on the returning tide are rapid, exceeding 1 °C per hour.

While the lowest individual temperature observed in 2009 was in the central zone at Buoy Key, the lowest average daily temperature was observed in the western zone at Johnson Key on the outgoing tide. This may indicate that the cold waters in the shallow interior of Florida Bay just east of Johnson Key flow through the western zone to the Gulf of Mexico. The cold water events at Johnson Key on January 22 and February 5 and 6, 2009, coincide with observations of the lowest stage levels of the year along the western zone, which is influenced by the Gulf of Mexico (-3.14 feet, NGVD29 at station JK). The temperature variability at Johnson Key is much less than at Buoy Key. The trend toward lower temperatures during January and February is consistent with less daytime heating observed in the Gulf of Mexico-influenced coastal stations in winter and increased influence from evaporative cooling on the shallow banks of the bay at night.

High temperature events are potentially damaging to benthic communities. For example, *Thalassia testudinum*, the dominant seagrass in Florida Bay, has an upper limit for thermal tolerance of 33 °C for up to a few weeks (Koch et al., 2007). In 2009, the highest average monthly temperature for all four zones in aggregate occurred in July and was within a narrow range at 31.68 ± 0.26 °C. This value for 2009 was within the 75th to 90th percentile of the historic range (Fig. 5). The shallower central and eastern zones (Fig. 5) presented at a slightly higher percentile relative to the historic range than did the western or southern zones (Fig. 4). The highest hourly temperature for the year was 36.89 °C observed in Trout Cove at station TC during the afternoon of July 17. No significant fish die-off or algal bloom was observed during this high temperature yet short duration event. This event occurred in a shallow region that rapidly cooled by several degrees within 24 hours. Specifically, water temperatures decreased overnight by more than 4 °C in just 9 hours resulting in nighttime high temperatures at TC, and at neighboring coastal station LM, of approximately 33 °C. While this temperature matched the thermal tolerance limit of *T. testudinum*, it doesn't appear that the high temperatures were maintained long enough to cause a die-off event.

Brown Pelicans (*Pelecanus occidentalis*) often can be seen diving from the air for fish or resting on the surface of the water.

NPS photo.

Dissolved Oxygen

Dissolved oxygen concentration reflects a balance between photosynthesis and respiration and is influenced, to a lesser extent, by diffusion at the sea surface. The concentration of dissolved oxygen in the water column affects the abundance and distribution of biota in a body of water. Threshold values for sub-lethal (5.0 mg/L) and lethal (2.0 mg/L) oxygen concentrations have been defined although the recent work recommends raising the definition of the lethal hypoxic threshold as high as 4.6 mg/L (see Vaquer-Sunyer and Duarte, 2008, for review). Dissolved oxygen wasn't being measured during the time period of this study; still, some information about dissolved oxygen in Florida Bay can be determined by calculating its solubility limit. The oxygen solubility limit, defined as the maximum amount of oxygen that can be dissolved into a seawater solution, was calculated for each station in the marine network. This limit has an inverse relationship with salinity and temperature, reaching its lowest value of the year when temperature and salinity are at their highest values. Oxygen solubility is calculated as:

$$lnC_o^* = 5.80818 + 3.20684T_S + 4.11890T^2_S + 4.93845T^3_S + 1.01567T^4_S + 1.41575T^5_S + S(0.00701211 + 0.00725958T_S + 0.00793334T^2_S + 0.00554491T^3_S) + 0.000000132412S^2$$

where:

C_o^* is the oxygen solubility limit in seawater, in mg/L;

S is the salinity, in mg/L; and

T_S is the scaled temperature, in ^oC (Garcia and Gordon, 1992).

The dissolved oxygen solubility limit provides insight into the time of year that oxygen limitation may play a critical role in ecosystem health. The dissolved oxygen solubility limit daily time series for 2009 for each zone in Florida Bay is shown in Figure 6. The annual pattern in the dissolved oxygen solubility limit, with a peak in February and a minimum in May, is visible across all zones. The lowest value of the year, 5.34 mg/L, was calculated for the central zone at Buoy Key on May 12 and resulted from a combination of high salinity and high temperature prior to the onset of the wet season. In contrast, slightly deeper regions of the bay in the western and eastern zones ranged from 5.7 to 6.0 mg/L during the same time period. During the wet season, the dissolved oxygen solubility limit increases slightly with decreasing salinity yet remains lower than mid-winter values due to high water temperature. Interestingly, due to lower salinity in the basins of the eastern zone, the dissolved oxygen solubility limit climbs during the summer months to levels higher than observed in the other three zones of Florida Bay. This may indicate a difference in the ability of waters in the eastern zone to support respiration in the absence of other confounding factors. Differences in the solubility limit throughout the year reveal the sensitivity of the physical system to the combined influence of temperature and freshwater flow and may have implications for understanding the effects of freshwater management decisions with respect to coastal ecology. At the end of 2009, plans were in place to enhance the monitoring network with dissolved oxygen sensors so that we may determine the O_2 saturation level, which is the ratio between the measured O_2 concentration in surface waters and the predicted O_2 solubility limit. O_2 saturation will then provide information about the ecological system as well as the physical system with respect to oxygen availability.

Tricolored Herons are a common sight in the mangroves, estuaries, lagoons, and salt marshes of Florida Bay.

Photo by William Perry.

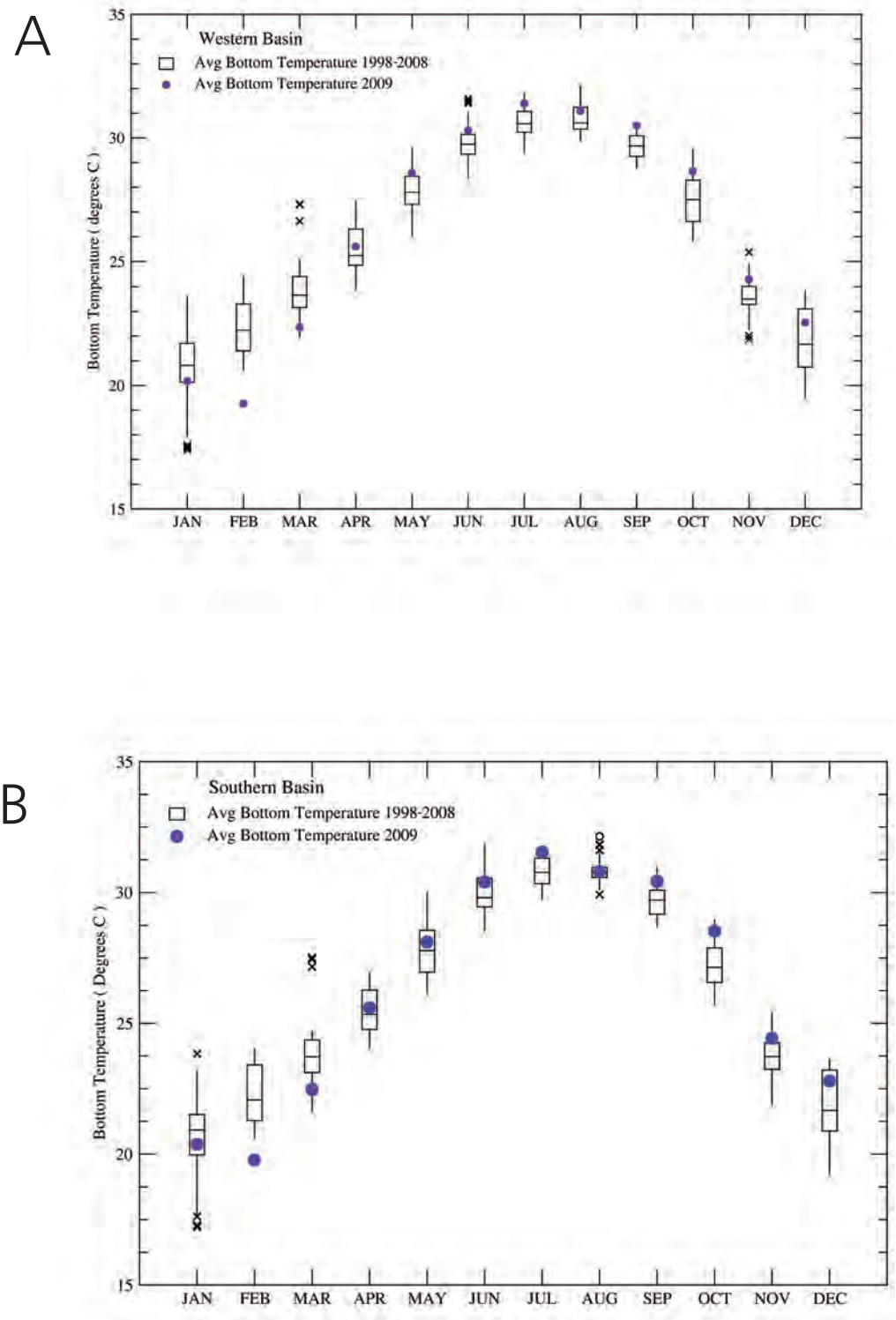

Figure 4. Temperature profile for the (A) western and (B) southern basins for 2009 overlaid on the statistical distribution of temperature data for the respective zone during 1998–2008.

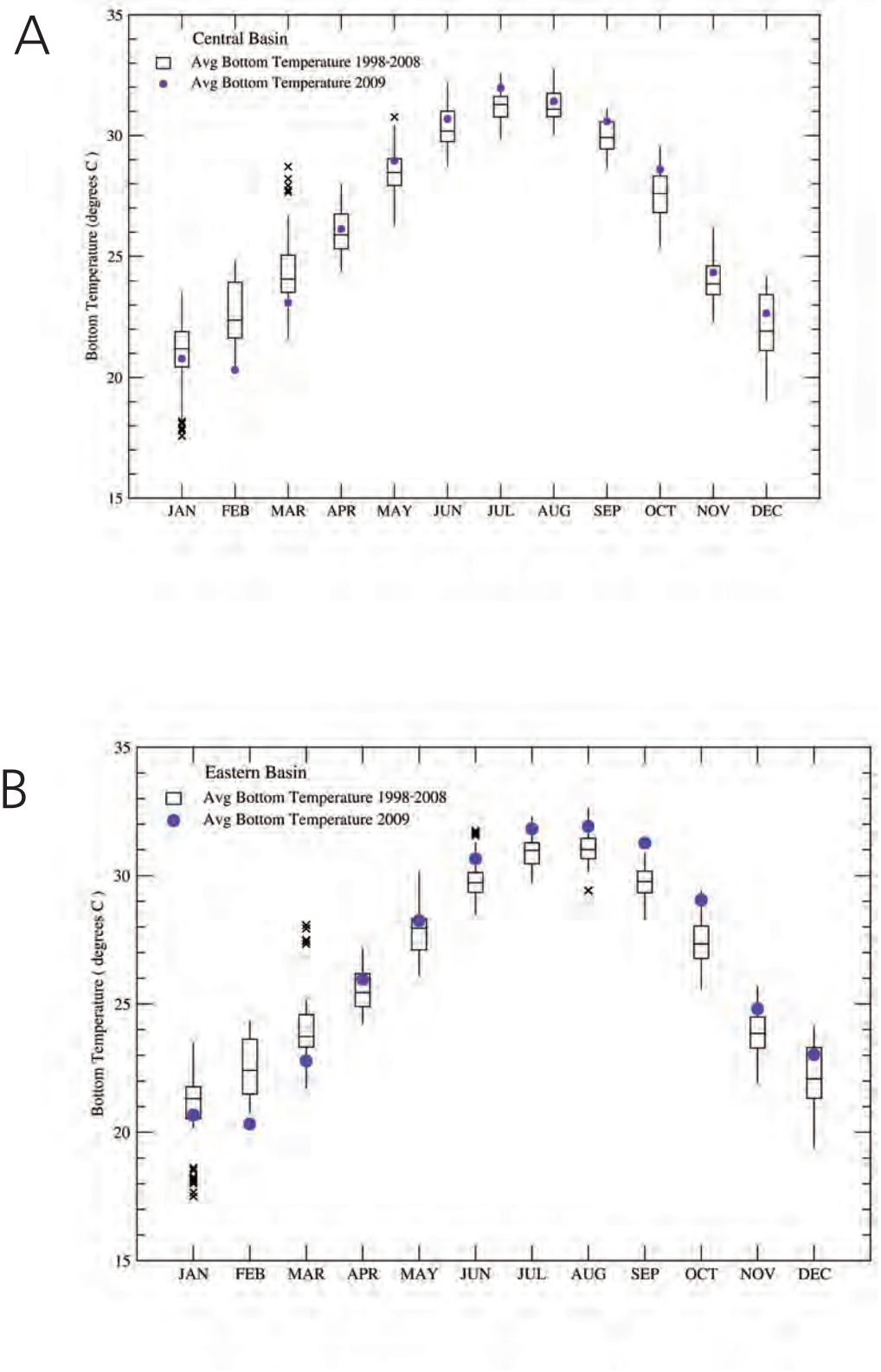

Figure 5. Temperature profile for the (A) central and (B) eastern basins for 2009 overlaid on the statistical distribution of temperature data for the respective zone during 1998–2008.

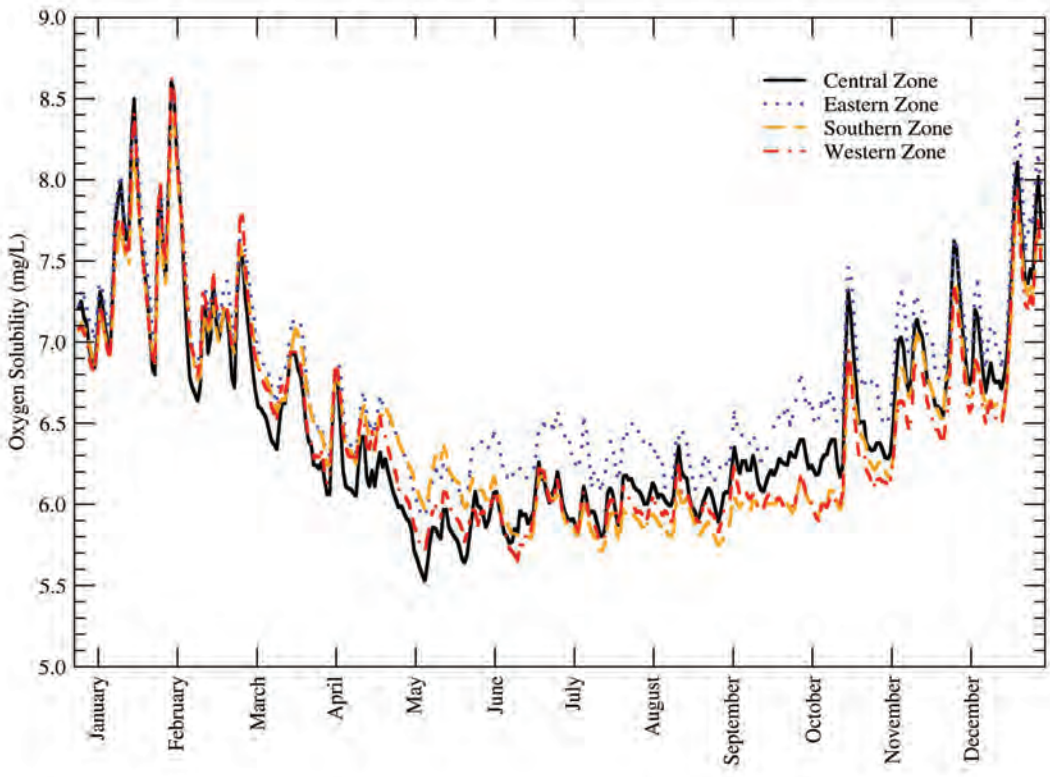

Figure 6. Dissolved oxygen solubility limit daily time series for each zone, 2009. (Note: Eastern Zone excludes station JB for this analysis).

Surface-water Flow

Surface water reaches Florida Bay in two forms, as either creek discharge at one of several locations with direct connection to the bay or as sheetflow over broad flat landscapes in more limited locations. Freshwater discharge can also be significant in a regional context, with freshwater outflows through the greater Shark Slough and Shark River system affecting coastal salinity on the western boundary of Everglades National Park and then being transported into western Florida Bay. In this report, our focus is on the relatively well-defined creek discharge for the northern boundary of the bay and its impact on salinity in the semi-isolated central and eastern basins. Consideration is given to regional influences on salinity in western Florida Bay where appropriate.

Discharge from the freshwater marsh to the coastal basins via creeks is influenced by the amount of freshwater that enters into the marsh region both from the L–31W system into Taylor Slough and from the lower C–111 canal and related structures into the eastern panhandle region. Flow through Taylor Slough is calculated from stage data at station TSB, near Taylor Slough Bridge, and from bi-weekly flow measurements for water passing through the culverts and bridges that cross under the main park road. Monthly total discharge data for Taylor Slough during 2009 relative to monthly discharge statistics for the period of record (1990–2009) is shown in Figure 7. The dataset shows that 2009 began with an extended dry period, with very low to zero flow from January through May. Following this, during the months of June through September, the median monthly flow was above the median for the period of record. Of these months, June and September were exceptionally high flow months, with median flow between the 75th and 90th percentile relative to the period of record. After this date, the median flow was closely matched to the median for the period of record even though the rainfall values for the months of November and December were well above the median rainfall for the period of record. On a monthly basis, the peak total freshwater discharge into Florida Bay occurred in the beginning of the 2009 wet season; however, a significant increase in discharge can be seen in December (Fig. 8). This is interesting as it is likely related to the large rainfall events occurring in November and December and subsequent water management releases that were pronounced in the eastern panhandle but not apparent in the Taylor Slough data.

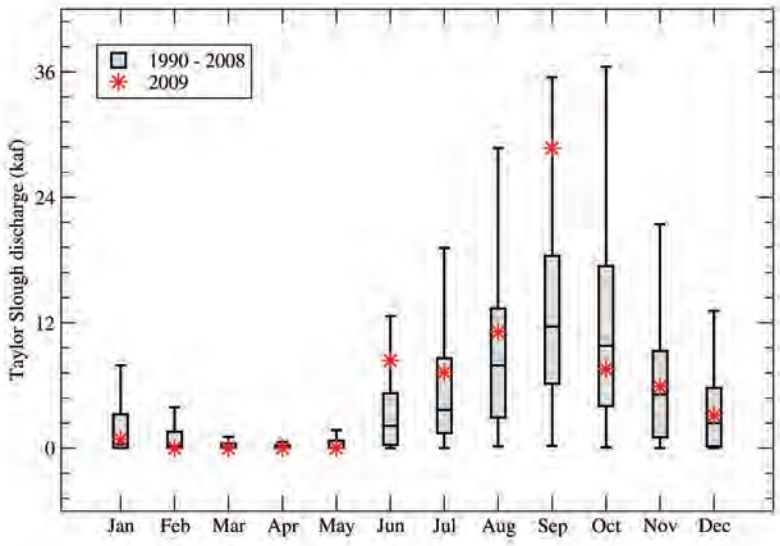

Figure 7. Relation of monthly Taylor Slough discharge for 2009 to distribution of monthly discharge values for the period of record.

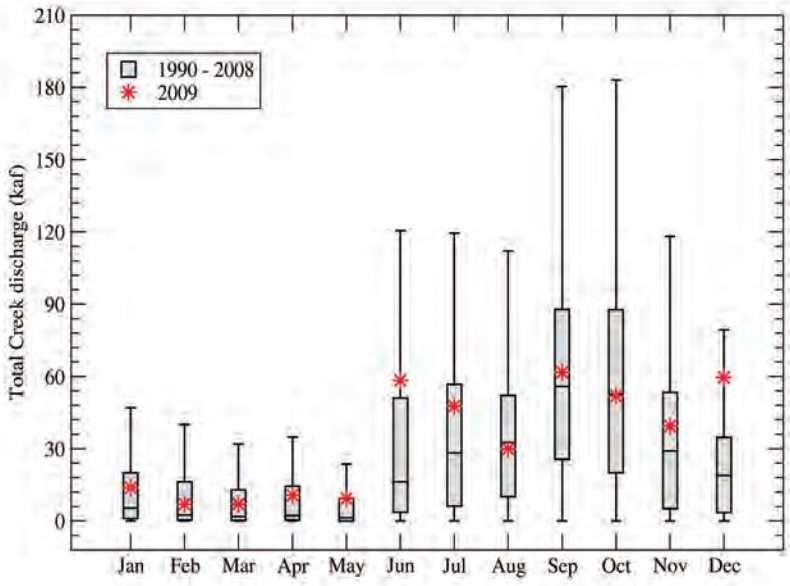

Figure 8. Relation of monthly total creek discharge into northern Florida Bay in 2009 to distribution of monthly total discharge values for the period of record.

For the eastern panhandle region, flow comes from Taylor Slough and the lower C–111 canal. The fraction of water from the lower C–111 canal can be partially quantified by calculating the difference in flow between S–18C and flow that exits at S–197. This quantity of water flows into groundwater or over the bank to the south along the southeast-trending section of the C–111 canal. This freshwater source adds to the freshwater provided by direct rainfall in the basin and flows out a series of creeks into the northeastern section of Florida Bay. These creeks, and the primary monitoring station for each, include Taylor River (TRE), East Creek (ECR), Mud Creek (MUD), Trout Creek (TROUT), Stillwater Creek (SWC), West Highway Creek (HCW), and East Highway Creek (HCE). Of these, Trout Creek provided the majority of the freshwater discharge to the region, 187.1 kaf or approximately 57% of the total 2009 creek discharge to the bay (Fig. 9).

The Florida population of North American Osprey increases during the winter months when many Osprey winter over in the plentiful feeding grounds of the Everglades. High visibility makes the Osprey a prime indicator species that can be used to monitor habitat conditions, fish populations, and overall environmental health. Photo by William Perry.

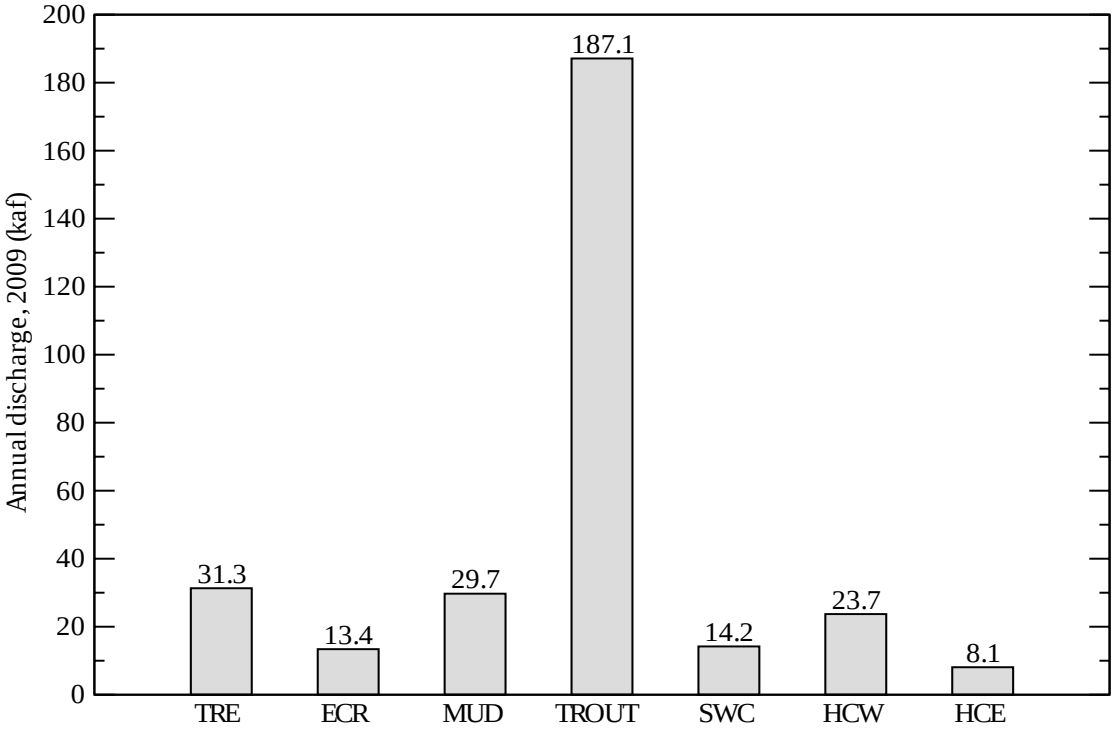

Figure 9. Annual discharge from seven creeks that flow into northern Florida Bay, 2009.

Salinity

Salinity has been identified as a restoration performance measure for Florida Bay, with guidelines established to (1) reduce the number of hypersaline events each year, (2) increase the frequency and spatial extent of lower salinity conditions in the bay, and (3) provide more stable conditions by avoiding rapid salinity decreases in the northeastern region of the bay (CERP–SEPM, 2008). The marine monitoring network stations have salinity sensors collecting hourly data accurate to 0.02 PSU located 1 foot from the bay bottom. The network was fully operational in 2009 with a total of 17 stations reporting hourly salinity more than 98% of the time. In Florida Bay, salinity is affected by precipitation, evaporation, exchange between basins and with the coastal ocean, and surface-water inflow, which is in turn affected by canal operations and controlled discharge events. While fresh groundwater discharge does not have a significant impact on salinity in Florida Bay (Corbett et al., 1999; Fitterman et al., 1999; Swart and Price, 2002), it is reasonable to infer that saline groundwater exchange may affect salinity variability. The current discussion begins with measured salinity in Florida Bay, followed by discussions of the impact of precipitation events and related overland flow, and closes with a discussion of the influence of canal discharge on salinity in the central and eastern regions of the bay.

The Southern Estuaries Performance Measure, developed by an interagency team in support of the Comprehensive Everglades Restoration Plan (CERP), provides a targeted range for annual average salinity for 17 zones covering the southern coastal region of the state including Florida Bay (CERP–SEPM, 2008). The plan specifies that the observed grand mean salinity, the mean of annual means, should be within the proposed range while the system is managed to minimize exceedances above the mean and yet provide for salinity excursions below the mean "…as long as unnatural pulse discharges of freshwater... are avoided…" (CERP–SEPM, 2008). The six CERP zones that overlap with regions specified in this report, the monitoring stations in each zone, the target salinity range, and the observed average salinity are provided in Table 2. For 2009, the annual average salinity for each zone was above the target range except in zone 5, the central region of the bay. In this region, the salinity was only 0.1 PSU below the maximum value for the target range. In some cases, for instance the Whipray Basin station (WB) and the Buoy Key station (BK) in the central region, the average daily salinity was above the guidelines 91% and 86% of the time, respectively (Fig. 10). Further, all stations experienced some time during the year when salinity was above the guidelines.

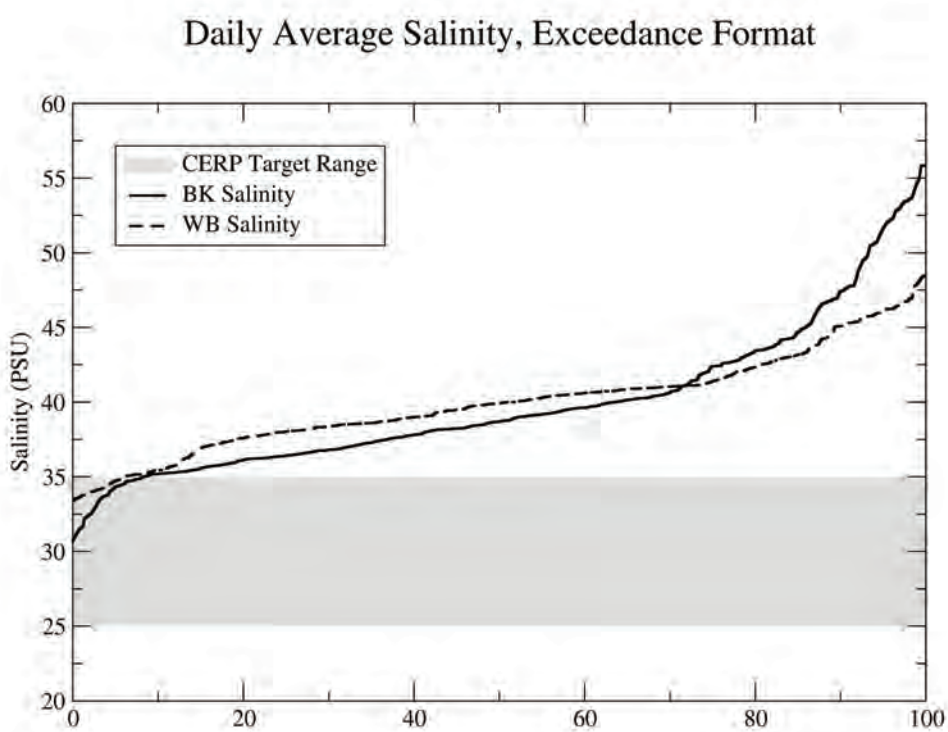

Figure 10. Relation of salinity at stations Buoy Key (BK) and Whipray Basin (WB) within central Florida Bay for 2009 to the CERP target salinity range for this zone.

Table 2. CERP zones within Florida Bay, associated monitoring stations, target salinity, and observed salinity for those zones in 2009.

Zone	Florida Bay Region	Monitoring Stations	Target Salinity Range (PSU)	Annual Average Salinity (PSU)
1	Eastern and Central	HC, LS, JB, LM	5 – 15, (except LM, 15-25)	20.6, (LM avg. = 28.57)*1
2	Eastern and Southern	BN, DK	15 – 30	35.6
3	Central	BK, WB, BA	25 – 35	39.3
4	Western	MK, JK, LR, PK	30 – 35	38.1
5	Central	TB, GB	15 – 35	34.9
14	Eastern	LB, BS	10 – 20 at LB; 15 – 30 at BS	28.9 at LB; 33.2 at BS

Hypersaline events, defined here as salinity greater than 40 PSU, are generally considered detrimental to the bay. Recurrent hypersaline events can lead to environments that are suitable only to hypersaline-tolerant species while shifting away from conditions favorable to estuarine adapted species. In 2009, hypersaline conditions were observed in the semi-isolated basins of Florida Bay and were most pronounced in the central zone. The highest salinity observed in Florida Bay in 2009 was 62.75 PSU at station GB (Garfield Bight) on the afternoon of May 1. This event is one of several short, less than 1 week, salinity peaks that occur after several days of consistent increases of approximately 0.8 PSU/day. The high salinity event on May 1 and the one that followed it on May 15 occurred during an extended hypersaline period lasting from February 18 through June 16. While long, at 118 days, it was not the longest period of hypersaline conditions observed within Florida Bay in 2009. The stations with the largest number of hypersaline days were station BA (Bob Allen Keys), at 165 days, and station WB (Whipray Basin), at 193 days above 40 PSU (Fig. 11). In these locations, the physical isolation and shallow environment combined to allow evaporation to exceed the quantity of freshwater delivered to the bay via precipitation and surface-water inflows. Farther to the east, fewer hypersaline days were observed, with Long Sound (LS) having 24 days and Blackwater Sound (BS) only 14 days above 40 PSU in 2009. These eastern stations are semi-isolated by a nearly continuous line of mangrove islands to their east and west and Key Largo to the south, with only minor connections to Barnes Sound via culverts or bridges that allow water to flow under highway U.S. 1. This region is connected to an intermittent freshwater source along its northern shore where freshwater enters from the eastern panhandle region of Everglades National Park.

Duck Creek monitoring station.
Photo by Steven Tennis, ENP.

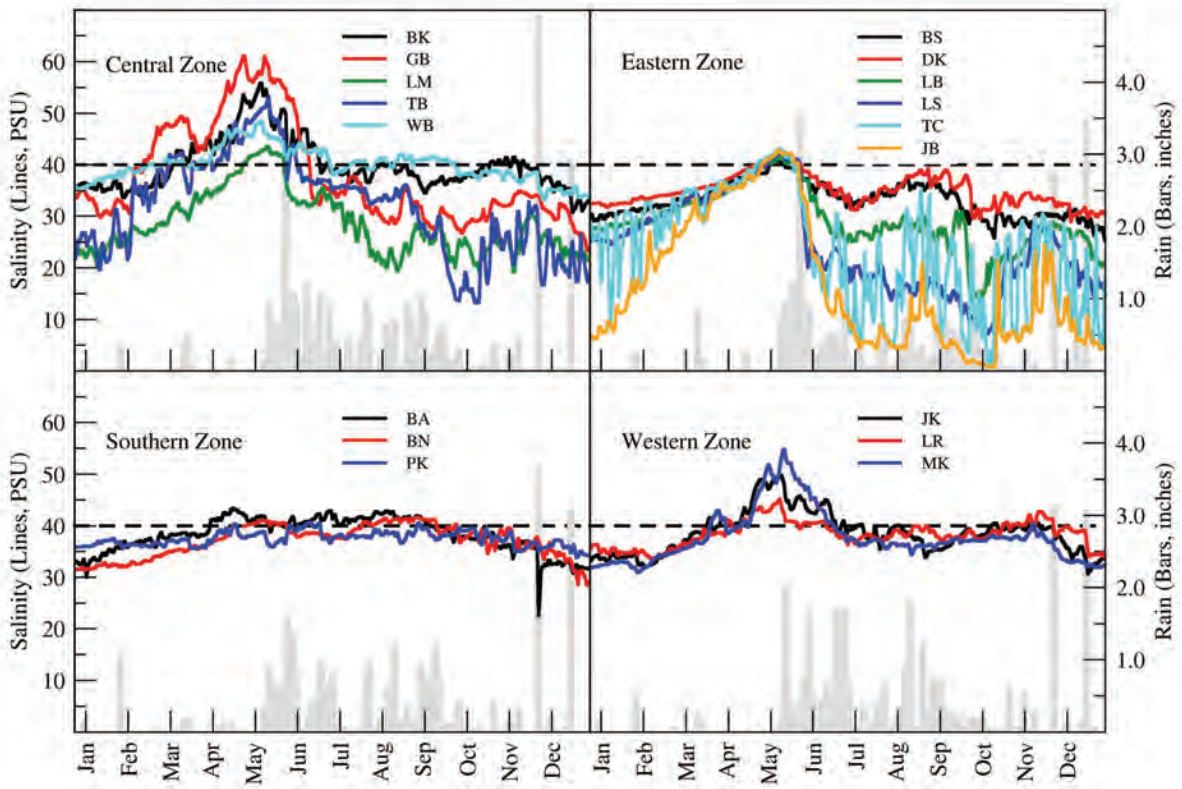

Figure 11. Daily salinity and rain values for each station organized by zone in Florida Bay in 2009. Horizontal dashed line indicates hypersalinity threshold.

An interesting rain event stands out in the data when comparing the southern zone salinity at station BA with the central zone salinity at station WB (Fig. 11). In November, an intense rain event with more than 3.5 inches of rain caused the salinity at BA to decrease by nearly 10 PSU, from 35 psu to 25 psu, and return to 35 PSU within 2 days. This same rain event delivered more than 4.5 inches of rain in the central zone, lowering salinity at station WB, 5 miles north-northwest of station BA, by approximately 5 PSU. The salinity at WB was impacted to a lesser extent by the rainfall but the effect on salinity was longer lived, with slower exchange rates in the central zone causing salinity to stay reduced for more than 7 days.

While exceedingly high salinity can be damaging, low salinity conditions, in contrast, are considered a desirable and necessary component of estuarine ecosystems (CERP–SEPM, 2008), even though rapid fluctuations in salinity can be detrimental to marine fish abundance (CERP–SE Fish Module, 2007). In Florida Bay, salinity fluctuations, their rate and duration, are a product of the connectivity of the basins in each zone. Several differences among zones can be observed in Figure 11. Starting with the eastern zone, high variability can be seen in the salinity data through the wet season. Some of the variability in salinity isn't directly correlated with rain events but rather is a product of flow from the neighboring marsh. As the dry season progresses in the beginning of the year, freshwater storage is depleted and salinity climbs to a more uniform hypersaline value at all stations. In contrast, in the western zone salinity is more uniform during the wet season while showing greater station-to-station variability at the end of the dry season. By the end of May, the salinity at MK is higher than the salinity at JK and LR. This may have occurred because the station is located in the shallowest portion of the western zone, where evaporation would have a relatively larger influence on salinity. The central zone stations show a combination of these two effects, with more variability due to rain in the wet season and higher salinity during the end of the dry season due to the enhanced impact of evaporation on these shallow basins. Within the central zone, station WB experiences the longest period of hypersalinity but also shows the least variability, likely due to its isolation and physical separation from the coast. Two large rain events occurred in the dry season at the end of 2009. Due to the isolated nature of the central zone, it is expected that these events would have large and lasting salinity impacts in this area. However,

in terms of lowest observed salinity, neither one of these precipitation events was large enough to reduce salinity into the CERP target range. Sub-35 PSU salinity was not observed until December 19, during the second of the two previously mentioned extreme and unseasonable precipitation events. No significant low salinity events occurred in which salinity was below the lower limit (25 PSU) of the target range, in the central region during 2009. Finally, the southern zone shows the least variation throughout the year at all stations, with no direct outflows from the coast to cause rapid salinity fluctuations and a slight removal from the highest precipitation zones, where convective storms can cause the large rain events and rapid salinity decreases.

Considering only the wet season of 2009, direct rainfall and regional surface-water flow affect salinity on different time scales and influence basins to different extents depending on the residence time of the basin and distance between the basin and the freshwater source. For example, comparing freshwater outflow from S–18C and Taylor River during the first wet season rain event of 2009, a reduction in salinity of almost 10 PSU was observed at the Little Madeira Bay station (LM) 7 days after the rain event. Little Madeira Bay is the receiving basin for Taylor River flow. In contrast, the reduction in salinity in Whipray Basin, which is located in a semi-isolated central basin, occurred much more slowly with lowering by the same 10 PSU over a period of nearly 5 months of combined outflow and rain events (Fig. 12). Qualitatively, this shows that salinity is influenced on shorter time scales where there is a direct freshwater source and on longer time scales in more isolated basins, where mixing between basins reduces the rate of transfer of freshwater across the bay. Considering the reduction in salinity at the Little Madeira Bay station (LM) in June relative to November, the reduction in salinity in June was sustained by continuous surface-water flow, whereas in November, the reduction in salinity was short-lived. During this time period, when flow decreased to less than 200 cfs, salinity increased and then decreased again as surface-water flow returned to rates above 200 cfs through the end of the year (Fig. 12).

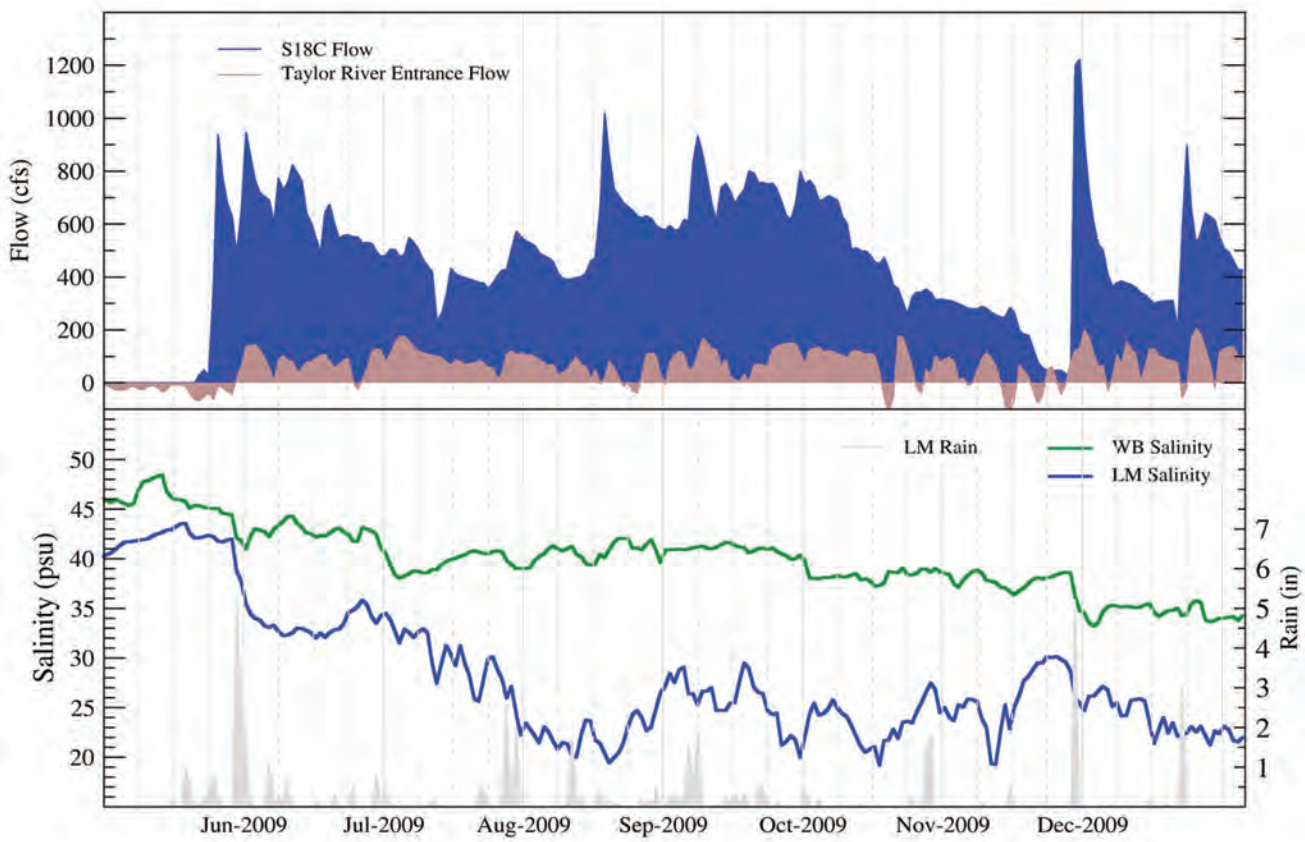

Figure 12. Influence of freshwater flow as gaged at S–18C and Taylor River and local precipitation on salinity in central Florida Bay, 2009.

FLORIDA BAY TREND ANALYSIS: 1990–2009

Precipitation

Salinity throughout the bay is influenced by the balance between precipitation, evaporation, surface-water input, and exchange with coastal water. These sources and sinks of freshwater have both seasonal and longer-term components, with the seasonal components primarily driven by differences in rainfall and evaporation. The tropical environment is broken into two seasons, a wet season that typically runs from June through October and a dry season from November through May. Both precipitation and evaporation are higher in the wet season, the latter related to the increased summer temperatures across the bay. Although wet-season rainfall is primarily driven by local convective events, the quantity of dry-season rainfall has been shown to be influenced by variations in global oceanic and atmospheric circulation patterns (Karamperidou et al., in press). No obvious long-term trend is discernible from these data; however, multi-year periods occur with significantly less precipitation than the overall annual average for the period of record. The wettest bay-wide average rainfall years in the period of record were 2007 at 51.16 inches, followed by 2001 with 49.85 inches. The driest years in the period of record were 2004 at 29.20 inches, followed by 1996 at 30.24 inches of precipitation. The value listed for 1993 was excluded from this ranking because it is based on only one station's data.

Variations in the amount of dry-season precipitation are correlated on a global scale with the El Niño Southern Oscillation (ENSO). ENSO events are defined by NOAA's Climate Prediction Center as occurring when the 3-month average sea-surface temperature departure exceeds 0.5 °C of the historic mean in the equatorial Pacific between 5° N–5° S and 170° W–120° W (National Weather Service, 2012). Higher ocean temperatures, seen during the positive phase of the ENSO cycle, are related to increases in rainfall across mainland Florida. The ENSO is a slowly developing feature that precedes, and perhaps influences, changes in atmospheric circulation. As such, it provides a mechanism to anticipate the relative quantity of rainfall expected in Florida Bay for a given upcoming dry season (Hagemeyer, 2006). For instance, dry-season rainfall totaling 16.17 inches was observed in the 2007 dry season while ENSO was in a positive phase. This value was above the average dry-season rainfall for the period of record of 12.3 inches. During positive ENSO periods, these higher dry-season rainfall totals have been observable in the data since the inception of the marine monitoring network (Fig. 13). Other significant dry-season rainfall years coinciding with positive phase signals in El Niño include events in 2003 and 2004 with 19.28 inches and 16.08 inches of rainfall, respectively; 1998 with 15.90 inches; and 1993 with 20.64 inches. The relationship between the ENSO index and dry-season precipitation in Florida Bay (1997–2009) and in the longer time series available in the neighboring slough (station Royal Palm, 1949–2009) is shown in Figure 13. Two vertical lines have been added to denote the ENSO positive/negative limits with the data points outside of this zone emphasized to indicate values where the ENSO signal expected to have an impact on precipitation values. The Florida Bay data show that, although dry-season rain is highly variable, precipitation during the period of record has never been above 9 inches when the ENSO index is in its negative phase or below 11 inches when the ENSO index was in its positive phase. On the basis of these data, dry-season rain on Florida Bay during the positive phase of an ENSO cycle has been approximately 13.3 ± 3.6 inches. It is also interesting to note that the offset between the trend lines in Figure 13 indicates that approximately 5 inches more dry-season precipitation is expected in the freshwater slough than in Florida Bay regardless of ENSO phase.

Primarily herbivorous, West Indian manatees (*Trichechus manatus*) graze on seagrasses and other aquatic plants, though they will occasionally also feed on fish.

Photo by Lori Oberhofer, ENP.

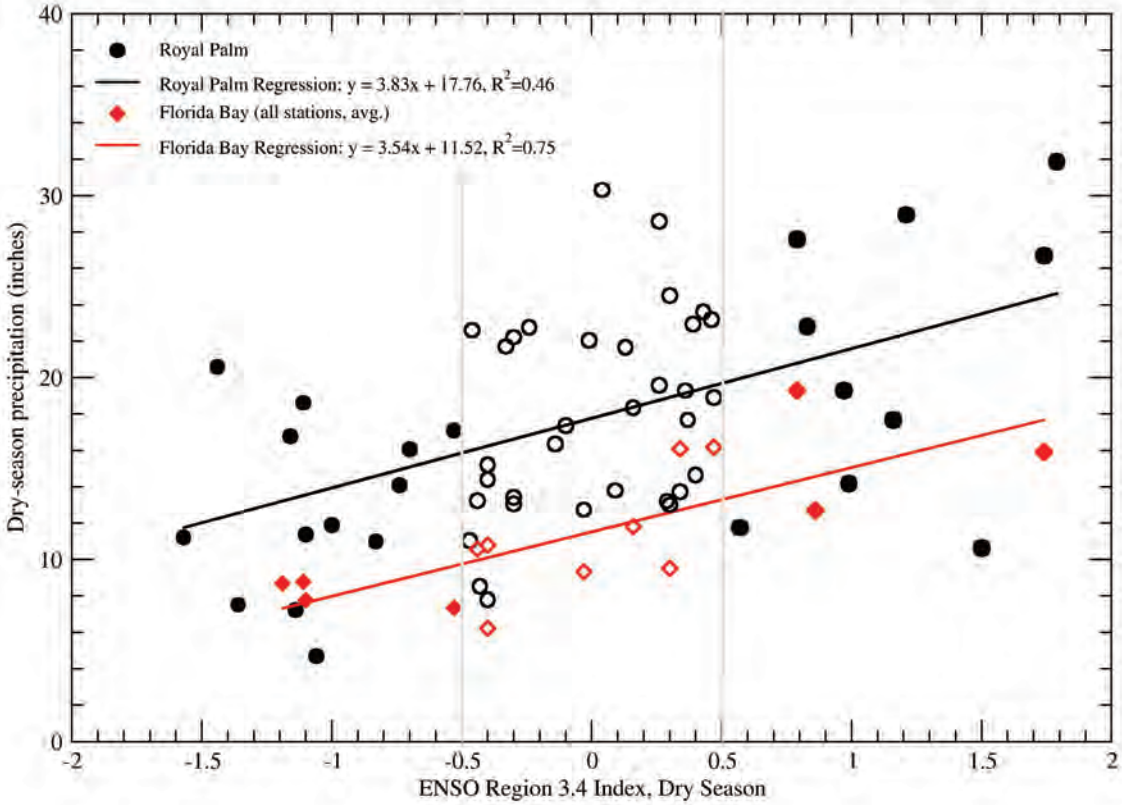

Figure 13. Relationship showing changes in dry-season precipitation as a function of ENSO signal. Solid symbols indicate periods when the ENSO phase is defined as positive (ENSO Index > 0.5) or negative (ENSO Index < -0.5).

Some general limitations should be considered prior to using the ENSO index as a predictor for precipitation in Florida Bay. First, individual tropical storms can have a large influence on the total annual rainfall, obscuring the subtle differences associated with changes in dry-season rain with high precipitation rates and amounts along the storm path. For instance, in 2003 and 2007, positive ENSO-related increases in dry-season rainfall contributed to a higher total annual rainfall of 49.75 inches and 51.16 inches bay-wide respectively (Table 3). In contrast, in 2001, while the ENSO index was neutral, as indicated by a value of -0.44 (Table 4) for the dry season, even with average dry-season rainfall the annual rainfall in Florida Bay was above average due to tropical-storm-related precipitation during the wet season.

The green turtle (*Chelonia mydas*) is one of five species of sea turtle that swim in Florida Bay and nest on its beaches. Adult green turtles are primarily vegetarians, with seagrasses and algae making up the bulk of thier diet. Adults average 350 pounds, and the upper shell averages 3.3 feet in length.

Photo by William Perry.

Evaporation

For this report, an estimate of evaporation in Florida Bay for 2007 was developed (see "Evaporation" in the "Florida Bay Status: 2009" section of this report). A ratio was then determined between the estimated evaporation in Florida Bay and time-series evaporation data collected at a station located at Forty Mile Bend in the northwestern part of Shark Slough. The resultant time-series evaporation estimates were then grouped into monthly values for use in determining the freshwater budget (see the "Freshwater Budget" section of this report). For 2001 through 2009, the average annual evaporation in Florida Bay was 44.8 ± 10.5 inches with no discernible multi-year trend. The large uncertainty associated with evaporation estimates makes it difficult to develop an accurate water budget and to determine the relative influence of freshwater sources on bay salinity with respect to other freshwater sources. Put in context, the 5.9 inches standard deviation for the estimated annual evaporation for 2001, extrapolated across the 2,200 km^2 of Florida Bay, equals 271 kaf of water, an amount roughly 2.5 times the 125 kaf creek discharge estimated as necessary to avoid hypersalinity in northern Florida Bay (Rudnick et al., 2006). Additional effort should be focused on reducing the uncertainty and, considering the importance of the shore effect on cloud cover and precipitation, extending the spatial coverage of evaporation measurements into the coastal zone.

The complicated interplay of currents, tides, winds and weather, topography, water density, salinity, and other physical and chemical factors makes for constantly changing conditions in Florida Bay.

Photo by Lori Oberhofer, ENP.

Table 3. Annual precipitation data by station through the period of record (1992–2009).

	Western			Central				
Year	**JK**	**LR**	**MK**	**BK**	**GB**	**TB**	**WB**	**LM**
1992	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
1993	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
1994	30.59	N/A	N/A	N/A	N/A	47.82	39.63	22.87
1995	44.18	N/A	N/A	N/A	N/A	41.27	46.67	42.26
1996	11.29	16.56	N/A	N/A	42.84	33.27	41.86	37.10
1997	45.76	27.21	15.72	13.25	41.14	37.03	50.54	40.00
1998	22.05	33.56	25.59	41.73	34.35	41.12	31.97	45.67
1999	49.27	50.84	55.44	42.90	54.78	46.56	47.38	34.15
2000	26.88	35.72	39.70	29.13	35.02	29.68	30.63	28.38
2001	51.03	52.20	48.83	51.79	59.49	49.26	51.87	52.08
2002	35.91	38.75	43.96	50.35	46.93	46.75	34.75	38.63
2003	50.48	65.28	41.65	47.19	53.12	63.41	58.22	46.51
2004	27.72	28.61	22.39	36.46	27.62	30.37	25.98	28.26
2005	33.21	32.08	16.75	37.82	39.20	51.32	47.89	44.71
2006	17.67	29.74	42.33	32.51	52.19	36.71	7.32	38.69
2007	28.75	40.46	45.70	48.25	55.94	50.41	50.77	59.57
2008	42.35	40.48	42.40	45.87	47.19	44.44	46.79	35.83
2009	39.78	38.72	34.40	39.89	47.13	45.33	31.90	50.49
Average	34.81	37.87	36.53	39.78	45.50	43.42	40.26	40.33
Standard Deviation	12.08	12.14	12.59	10.48	9.29	8.75	12.70	9.55

Sometimes spelled "cay" or "caye," a key is a small, low-elevation, sandy island formed on the surface of an ancient coral reef.

Photo by William Perry.

Florida Bay is separated into many basins by shallow banks and small islands.

Photo by William Perry.

Table 3. Annual precipitation data by station through the period of record (1992–2009)—Continued.

		Eastern						Southern			
Year	**JB**	**TC**	**DK**	**HC**	**LS**	**LB**	**BS**	**PK**	**BA**	**BN**	**Total**
1992	48.39	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	48.39
1993	29.88	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	29.88
1994	56.74	18.18	N/A	N/A	28.25	N/A	N/A	25.48	N/A	31.72	33.48
1995	49.15	43.70	49.26	41.63	29.91	N/A	N/A	35.33	N/A	42.42	42.34
1996	33.23	38.56	19.48	28.83	49.44	24.05	30.01	18.56	15.22	43.49	30.24
1997	32.96	54.91	58.70	7.01	56.76	6.18	6.57	26.46	26.33	42.01	32.70
1998	37.36	46.10	21.26	29.58	40.95	N/A	N/A	39.35	48.16	41.58	36.27
1999	27.73	46.50	38.03	42.23	11.51	5.46	24.57	39.15	56.63	47.82	40.05
2000	12.51	36.08	37.15	36.37	38.78	47.91	46.86	35.50	36.45	38.59	34.52
2001	28.30	44.50	42.86	39.51	50.53	58.83	48.55	62.21	58.68	46.86	49.85
2002	22.53	47.26	30.37	44.33	47.14	51.87	48.94	37.02	30.00	45.27	41.15
2003	22.64	46.85	46.00	48.87	42.93	48.01	46.28	60.55	63.53	44.05	49.75
2004	24.18	31.91	31.35	30.47	28.85	34.88	20.52	30.83	34.25	30.90	29.20
2005	44.98	44.59	30.85	34.58	40.79	62.17	41.70	36.34	40.79	45.79	40.31
2006	31.80	32.12	30.80	45.29	39.22	36.54	36.38	33.59	45.03	34.10	34.56
2007	42.28	48.14	55.56	58.23	61.22	68.88	63.38	45.58	41.94	55.85	51.16
2008	19.82	31.41	31.07	38.86	38.29	36.82	29.29	34.90	44.39	28.81	37.72
2009	40.85	42.83	43.20	41.44	41.54	43.27	40.62	39.13	33.70	37.63	40.66
Avg.	33.63	40.85	37.73	37.82	40.38	40.37	37.21	37.50	41.08	41.06	39.01
St. Dev.	11.67	9.00	11.51	11.50	12.04	19.57	14.86	11.31	13.20	7.13	7.14

Little Rabbit Key in Florida Bay.

Photo by William Perry.

A connectiing pass between two islands in Florida Bay.

Photo by William Perry.

Table 4. Dry-season ENSO Region 3.4 Index (ONI-ERSSSTv3b, 2011) and dry-season total precipitation in Florida Bay and in the neighboring marsh at the Royal Palm station, sorted by ENSO index.

[Shaded regions indicate when the ENSO phase is defined as positive (ENSO Index > 0.5) or negative (ENSO Index < -0.5).]

	Dry-season Values, sorted by ENSO Index		
Year	**ENSO Region 3.4 Index**	**Florida Bay precipitation (inches)**	**Royal Palm precipitation (inches)**
2000	-1.19	8.7	15.1
1999	-1.11	8.8	18.6
2008	-1.10	7.8	11.4
1996	-0.53	7.3	17.1
2001	-0.44	10.6	13.2
2006	-0.40	6.2	14.4
2009	-0.40	10.8	15.2
1997	-0.03	9.3	12.7
2002	0.16	11.8	18.3
1994	0.30	9.5	16.5
2004	0.34	16.1	13.7
2007	0.47	16.2	18.9
2005	0.57	*	11.7
2003	0.79	19.3	27.6
1995	0.86	12.7	25.5
1998	1.74	15.9	26.7

The * in Florida Bay rain for 2005 is due to limited data available as a result of extensive hurricane-related station damage.

Surface-water Flow

Freshwater enters Florida Bay primarily from Taylor Slough via Taylor River and its related tributaries, and also through a set of creeks along the eastern panhandle region downstream of the C–111 canal. The annual contribution of freshwater to Florida Bay from eight major coastal creeks for 1995 through 2009 is shown in Table 5. The highest total discharge of 454.5 kaf was observed in 2005, a year impacted by Hurricanes Katrina, Rita, and Wilma. In comparison, 2009 creek discharge was 324.1 kaf, the fifth highest in the 14-year period of record. This input was approximately 16% of the 1,835 kaf of freshwater introduced by rainfall from 40.66 inches of rain across Florida Bay during the same year.

Surface-water flow has an inverse relationship with salinity and this relationship is more pronounced near outflow points than at stations a greater distance from the freshwater source. Salinity within coastal basins is influenced to a greater extent than the bay as a whole because of the physical barriers imposed by shallow banks and narrow passes. These restrictions on flow between basins create a lag in the timing between freshwater input along the coast and observed changes in salinity in basins farther from the coast. To determine the extent that coastal freshwater discharge influences salinity across the basins in the bay, a lagged correlation analysis was performed between discharge data from the creek stations and salinity at each station within Florida Bay. General trends in the relationship were observed by analyzing the change in salinity

Table 5. Annual discharge (in kaf) for the eight primary creeks that connect into Florida Bay, 1995–2009. (Source: DBHydro Database, 2010)

YEAR	MCC	TRE	ECR	MUD	TROUT	SWC	HCW	HCE	TOTAL
1995	null	32.3	null	34.8	null	null	null	null	101.1
1996	16.3	17.6	null	20.6	165.0	null	39.9	null	259.4
1997	6.2	19.7	null	15.9	171.1	null	45.6	null	258.5
1998	-9.7	30.8	null	18.8	138.1	null	37.9	null	215.9
1999	20.2	37.9	null	32.3	186.9	16.5	38.6	null	332.4
2000	-1.9	23.3	null	9.9	118.7	5.4	29.1	null	184.5
2001	24.0	28.5	null	26.3	190.5	4.3	36.5	64.9	375
2002	30.3	35.3	null	29.6	171.2	8.6	36.2	31.9	343.1
2003	23.6	38.2	null	29.6	125.9	11.9	29.3	22.9	281.4
2004	11.2	21.2	null	15.3	54.1	4.6	19.8	5.5	131.7
2005	41.0	42.1	null	46.5	236.0	15.7	49.4	23.8	454.5
2006	27.6	29.1	37.5	25.3	79.0	6.6	28.3	8.2	241.6
2007	22.7	28.1	24.2	23.3	125.9	3.8	32.9	12.4	273.3
2008	15.4	17.1	8.6	18.1	164.8	4.2	22.6	13.3	264.1
2009	15.3	31.4	21.3	29.9	174.2	14.2	23.3	14.5	324.1

after the onset of freshwater discharge at the beginning of the wet season. Salinity at the station within Long Sound (LS) in northeastern Florida Bay showed a weak inverse correlation (R^2 = 0.67) with flow at structure S–18C at a lag of 9 days. Farther downstream in the system at the Little Blackwater Sound station (LB), the correlation is lower (R^2 = 0.58) and the lag extends to 27 days. Beyond that, the direct correlation between freshwater outflow and salinity reduction is not well defined but appears to show a general trend of reduced salinity within 2 months after a large freshwater discharge event. This relationship is obscured by variations in salinity due to direct rainfall within the basins. Despite being a primary source of freshwater to the bay, correlation analysis found the influence of flow from Taylor River south of TRE on salinity to be much weaker, with R^2 values never going above 0.30 for any station, even those closest to the freshwater source. This reduced correlation between outflow and salinity within the central region of the bay is likely a function of the distance between the outflow and the salinity monitoring stations and the decreased exchange across the shallow banks in the central zone of the bay.

For coastal stations influenced by freshwater discharge there is an inverse exponential relationship between the freshwater discharge flow rate and the observed decrease in salinity. The relationship is asymptotic, showing diminishing returns in terms of salinity reduction for associated increases in freshwater discharge. In eastern Florida Bay, outflow at Highway Creek West influences salinity in Long Sound and farther downstream in Blackwater Sound to different extents (Fig. 14). For Long Sound, the direct receiving basin for Highway Creek, the discharge and salinity data indicate that a flow rate of 100 cfs can reduce the salinity from marine conditions to 13 PSU, a reduction of approximately 22 PSU. An additional 100 cfs discharge only reduces salinity an additional 3 units on average. It appears that unusually high flow rates, above 300 cfs, are required to make salinity approach or become lower than 9 PSU. While uncommon, the historic record at Long Sound shows salinity was below 9 PSU 18% of the time over the period of record for flow data (1995–2009). For Long Sound, this relationship defines expectations in terms of salinity reduction from increased freshwater flow and coastal rehydration efforts. A similar relationship exists farther downstream at Blackwater Sound (Fig. 14, blue curve), with the point of diminishing returns occurring at higher salinity due to increased distance from the freshwater source, increased volume of the basins, and increased marine influence through mixing with neighboring basins. In the case of the Blackwater Sound freshwater flow to salinity analysis, the relationship establishes an average salinity value near 27 PSU as freshwater discharge from Highway Creek West approaches 300 cfs.

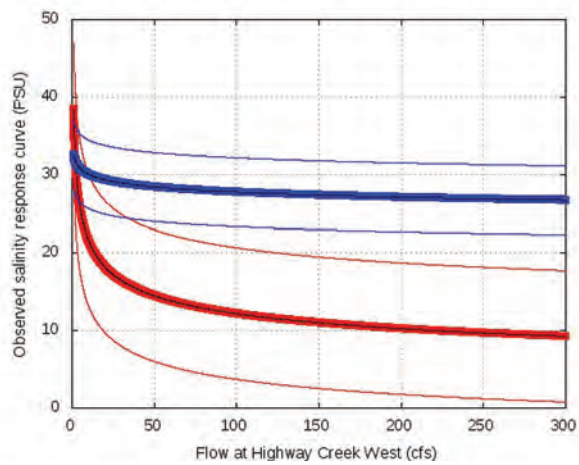

Figure 14. Relation of salinity to freshwater flow in Blackwater Sound (blue) and Long Sound (red) in eastern Florida Bay, 1995–2009.

Salinity

Salinity drives ecology on short time scales, with upper and lower limits defining ecological niches affecting the distribution of species and the viability of populations in Florida Bay. Long-term trends can influence the relative success of individual species with, for example, changes in the benthic seagrass community being perhaps the most likely outcome of a long-term trend in salinity. The following figures show salinity data from 1990 to 2009 for each region: western zone (Fig. 15), central zone (Fig. 16), eastern zone (Fig. 17), and southern zone (Fig. 18). In each figure, the upper plot contains a time-series of daily salinity data for the region, including 180-day and 3-year running averages, to reveal annual variability and long-term trends. The lower pane in each figure is an annual box and whisker plot for each region, providing the median, 25th and 75th percentile described by the box, and the 10th and 90th percentile described by the whiskers. Each region's data represent the average of that zone's stations except western Florida Bay, where only one station had salinity data for the entire period. In this case, the individual station at Johnson Key (JK) was used by itself as an indicator of the conditions within that zone.

South Florida is the only place in the United States where American crocodiles (*Crocodylus acutus*) (above) coexist with American alligators. Photo by William Perry.

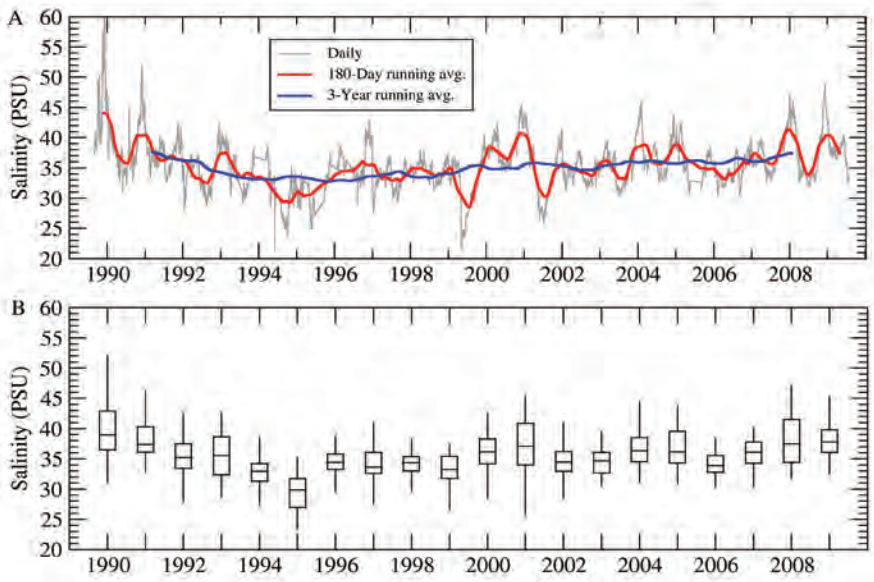

Figure 15. Salinity data for station JK in western Florida Bay showing (A) 180-day and 3-year running averages and (B) statistical distribution of salinity data for each year.

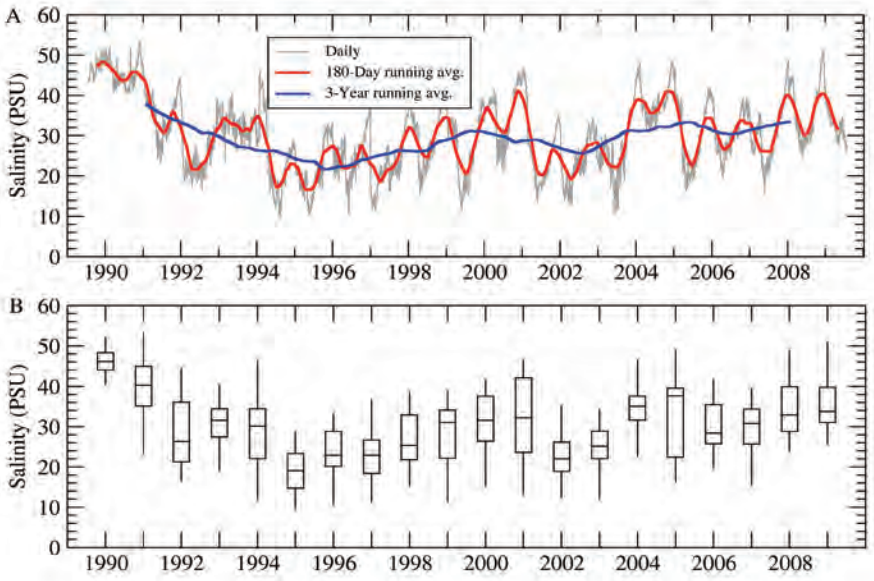

Figure 16. Salinity data for an aggregate of five stations in central Florida Bay showing (A) 180-day and 3-year running averages and (B) statistical distribution of salinity data for each year.

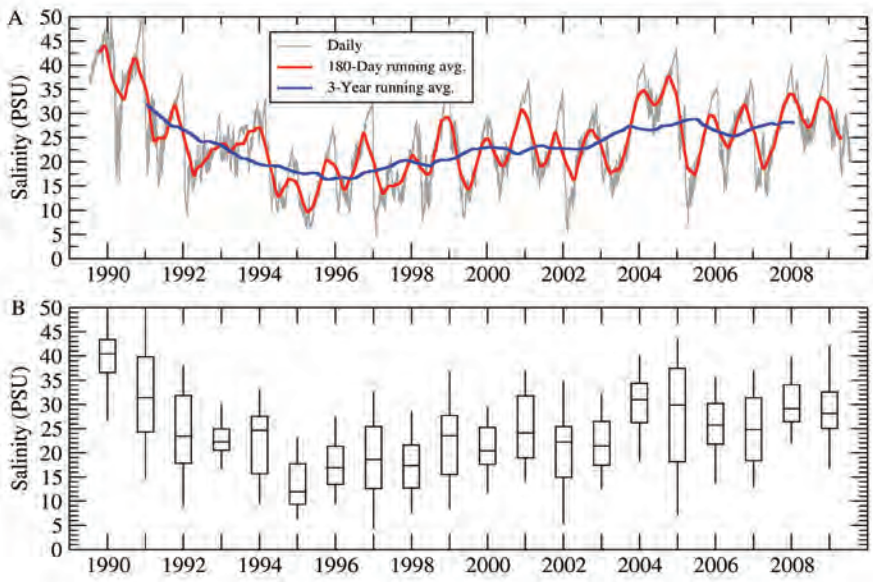

Figure 17. Salinity data for an aggregate of seven stations in eastern Florida Bay showing (A) 180-day and 3-year running averages and (B) statistical distribution of salinity data for each year.

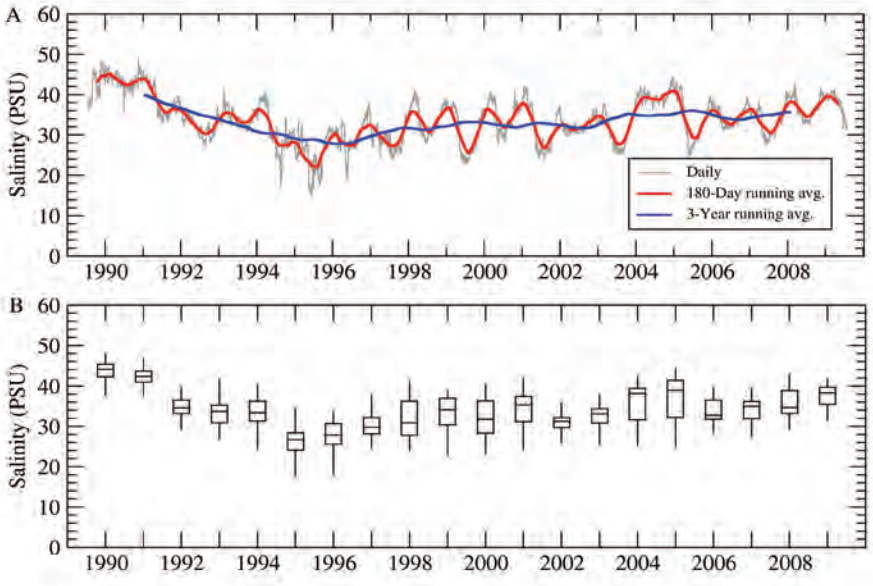

Figure 18. Salinity data for an aggregate of three stations in southern Florida Bay showing (A) 180-day and 3-year running averages and (B) statistical distribution of salinity data for each year.

Each region shares a similar trend in salinity, with the highest mean and largest range observed in 1990, followed by a decrease during the wetter-than-average rainfall years of 1994 and 1995. Salinity then increases from 1996 through 2009, with the rate of change being more pronounced in the semi-confined basins of the central and eastern zones. This trend is interesting since these semi-enclosed basins are direct recipients of creek discharge and, while variable, the outflow from these creeks increased over the last 4 years (Table 5). Increased freshwater flows would be expected to cause decreases in coastal salinity. A review of the relative contributions to the freshwater budget is included in the "Freshwater Budget" section of this report to investigate this anomaly. The seasonal signal in salinity in the basins can be observed in the 180-day running average salinity in the upper graph of Figures 15 through 18. For western Florida Bay (Fig. 15), the higher-than-average rainfall years of 1994 and 1995 are marked by the lack of dry-season increases in the 180-day running average salinity. This is also the case for 2006 when the previous fall's hurricane events supplied large amounts of rainfall to the area.

The amount of gaged surface-water flow is small relative to inputs from rainfall. Still, the timing of surface-water discharge has been recognized as critical in avoiding salt-water intrusion into the coastal systems from the bay and in preventing hypersalinity in the dry season. The Minimum Flows and Level (MFL) provision enacted December 12, 2006, in Chapter 40E–8 of the Rules of the South Florida Water Management District, Minimum Flows and Level Criteria (SFWMD, 2008) states that a salinity exceedance has occurred when "… the average salinity over 30 or more consecutive days exceeds 30 parts per thousand at the Taylor River salinity monitoring station… " and a salinity violation has occurred if there are exceedances "… during each of two consecutive years, more often than once in a ten-year period." The first exceedance since this provision has been in effect was in 2008 and it was followed by another exceedance in 2009 (Fig. 19). The trend toward higher salinity in the coastal basins downstream from the Taylor River outflow could indicate increasing frequency of high salinity events within the river. A review of the conditions through the last decade indicates that one violation of the MFL criteria would have already occurred had the rule been in place prior to 2004. By MFL criteria, the suggested annual flow levels have been met and yet salinity exceedances have occurred at the Taylor River station (TR), indicating a need to reevaluate the timing and distribution of freshwater flow in the flow:salinity relationship used to develop the criteria.

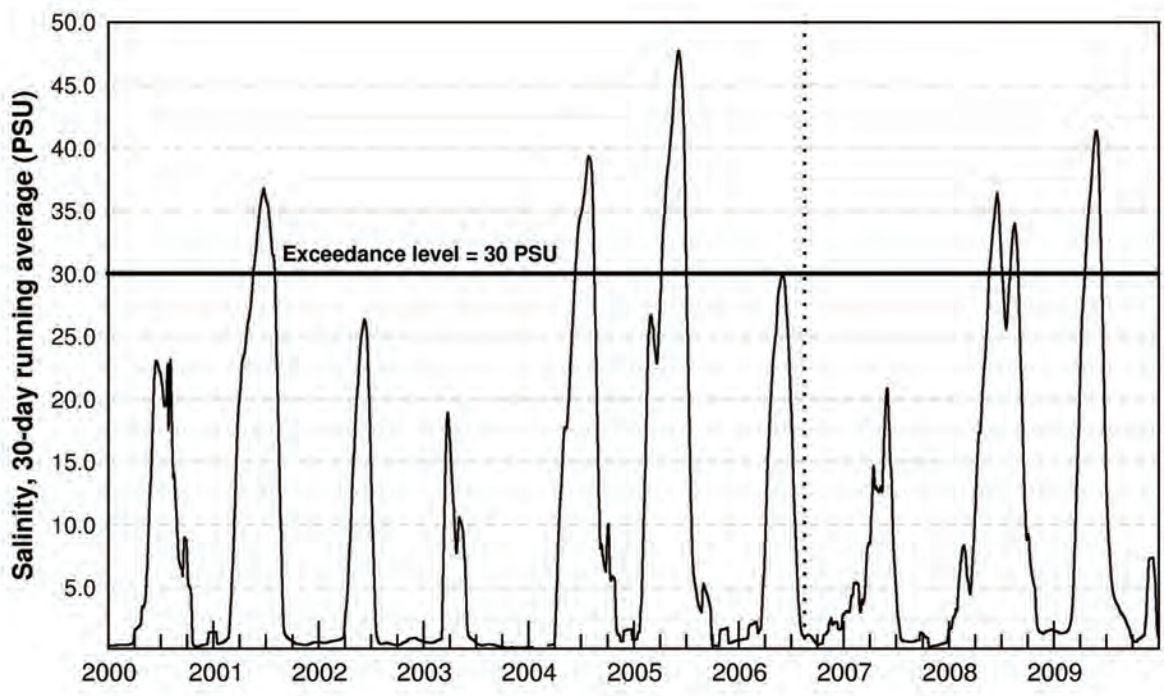

Figure 19. Salinity at station TR in Taylor River (2000–2009) with line indicating exceedance level as defined in SFWMD minimum flows and level criteria, 2008.

Analysis of stage differences between the marsh and the bay provides an alternate method of looking at drivers of salinity at this location. Salinity at TR increases as the stage at the Little Madeira station (LM), downstream, approaches or surpasses the stage at station E146, upstream (Fig. 20). The level differential shown is based on weekly stage data, including data that are affected by wind or seasonal tidal events. The implication is that salinity at TR is a function of the stage differential between the marsh and the coastal basins regardless of annual freshwater marsh to ocean flow volumes. In the short term, salt-water intrusion into the Taylor River may be reduced by maintaining a higher stage in Taylor Slough from July through November, as needed to maintain an appropriate head gradient when bay water levels are experiencing seasonal high levels. In the long term, sea-level rise is expected to continue, with the water level in Florida Bay increasing (see "Sea Level" section of this report). The appropriate stage for the marsh will need to be periodically reviewed and increased as necessary to avoid salt-water intrusion into Taylor River and the freshwater Everglades.

Freshwater Budget

Salinity is ultimately driven by the balance of freshwater sources and sinks within Florida Bay. Freshwater enters Florida Bay by precipitation, sheetflow, streamflow, and to an unknown but likely small extent by groundwater flow. Freshwater exits Florida Bay primarily by evaporation but also, to a lesser extent, by outflow or mixing along its southern or western boundaries. A combination of evaporation, precipitation, and freshwater streamflow data from 2000 to 2009 was used to produce a monthly net freshwater flux estimate for the bay. For precipitation and evaporation, the average monthly rates were extrapolated across the 357 k-acre area of the bay using the weighted Theissen polygon method to determine a representative monthly annual time series. For streamflow, the freshwater budget included salinity and flow measurements made at nine discharge locations along the northeastern border of the bay. The salinity data from the USGS streamflow-gaging stations (Hittle et al., 2001; Data source: DBHydro

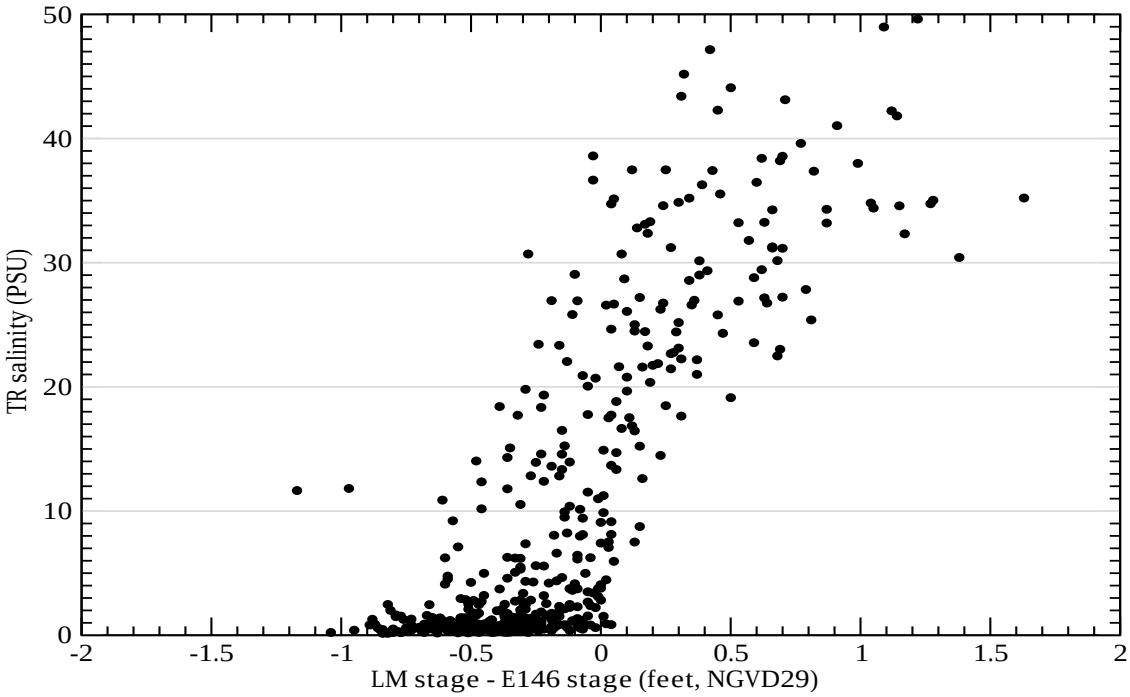

Figure 20. Salinity at Taylor River station TR as a function of difference between water level at the Little Madeira station LM, downstream of station TR, and station E146, upstream of station TR.

Database, 2010) were used to correct the discharge volume to represent only the freshwater component of the stream discharge. The net freshwater flux (*FW*, units = kaf per month) was then calculated as the sum of precipitation (*P*) and the freshwater fraction of surface water discharge ($Q_{in, fresh}$) less the freshwater losses to evaporation (*E*):

$$FW_{net} = (P_{in} + Q_{in, fresh}) - E_{out}$$

The freshwater fraction of surface water discharge is:

$$(Q_{in, fresh}) = Q_{total} \times \{1 - S_{obs}/S_{ref}\}$$

where:

Q_{total} is the total streamflow;
S_{obs} is the salinity of the streamflow; and
S_{ref} is set to 35 PSU to represent marine conditions.

Results show the typical wet- and dry-season variation in the monthly precipitation values with the wet season maintained from June through September. For evaporation, there was an increase in rate associated with the warmer months of the year with evaporation reaching its maximum value in May (Fig. 21). The net freshwater flux is negative, with evaporation exceeding precipitation, from January through May. The net freshwater flux then becomes positive during the wet season from June through September and returns to negative for the remainder of the year. This is largely driven by changes in precipitation; however, an additional streamflow component increases shortly after the start of the wet season but doesn't peak until October. The lag between the start of the wet season and the start of significant freshwater flow from the coastal streams is related to the quantity of water required to flood the basin within the region. Freshwater discharge increases after the marsh has flushed out the salt water that had entered during the previous dry season. A cumulative freshwater budget plot is helpful in highlighting the relative magnitude of evaporation (loss of 1.9 million acre-feet), precipitation (gain of 1.5 million acre-feet), and the much smaller component attributed to streamflow (gain of 0.17 million acre-feet) (Fig. 22).

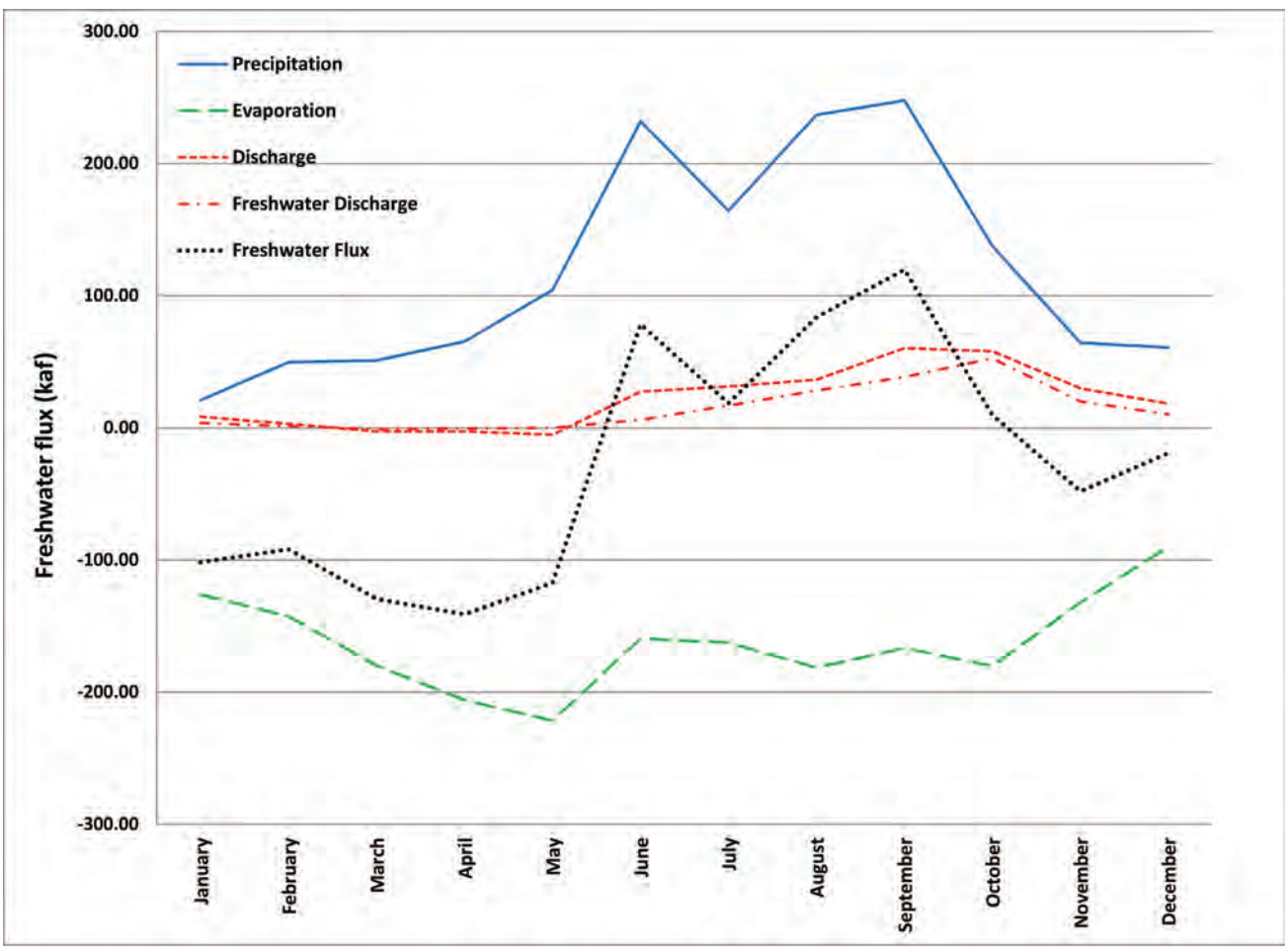

Figure 21. Time series showing average monthly freshwater flux to Florida Bay due to precipitation, discharge, and losses due to evaporation, 2000–2009. Net freshwater flux (black) shows seasonality with net loss during the dry season and net gain during the wet season.

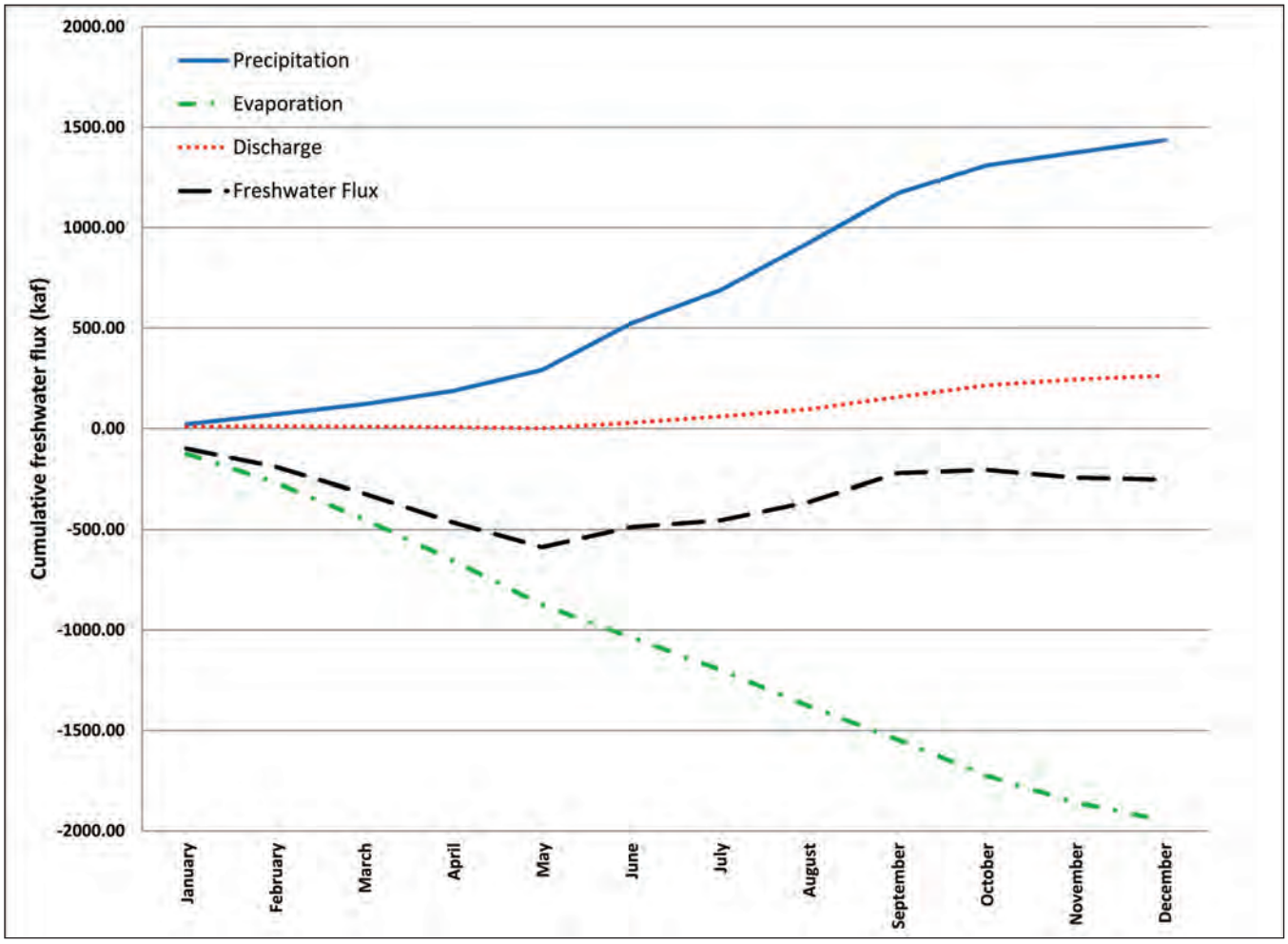

Figure 22. Time series showing cumulative monthly freshwater flux to Florida Bay, 2000–2009. Net freshwater flux (black) shows a loss of freshwater during the dry season and a gain of freshwater during the wet season, ending with a net loss on average over the course of the year.

The year-to-year relationship between dry-season salinity and net dry-season freshwater flux was examined. Although there is no trend in the net dry-season freshwater flux, there is a clear trend in dry-season salinity (Fig. 23). Furthermore, there is high variability in net dry-season freshwater flux that is only occasionally reflected in the year-to-year change in average dry-season salinity. For instance, between 2004 and 2005 there was a reduction in freshwater input observed during the dry season while there was also an increase in salinity within the eastern zone. This year-to-year relationship was not consistent as can be seen by looking at the change between 2006 and 2007 where the freshwater flux increased (less negative on the graph) by more than 500 kaf and yet dry-season salinity in the eastern zone also increased by more than 5 PSU. Overall, the variations observed in dry-season salinity are only partially explained by the variation in dry-season freshwater input. It remains to be seen if the general upward trend in dry-season salinity in the last decade is part of a longer-term cycle in precipitation-driven freshwater supply.

The resultant long-term trend toward increasing dry-season salinity in the central and eastern zones during the last decade is likely to be the result of several factors, some of which are relatively well quantified while others are largely unknown. Among these factors, long-term trends in the transfer rates between basins may have an important yet complex relationship with the trend in salinity. It would be expected that a more isolated basin would experience larger salinity increases during the dry season as evaporation exceeds freshwater input. In an isolated basin, this increase in salinity would not be moderated by mixing with lower salinity waters transferred in from coastally influenced basins. This expectation is supported during dry periods such as early 2009 when the salinity at BK, a very shallow and isolated basin, increased 18 PSU between January and May while salinity at both WB and BA, relatively less isolated basins to the south, increased by only 10 PSU during the same time period. The existence of trends in exchange rates and their causes if they exist between basins is unknown; however, transfer could be affected by subtle changes in bank heights due to sedimentation or

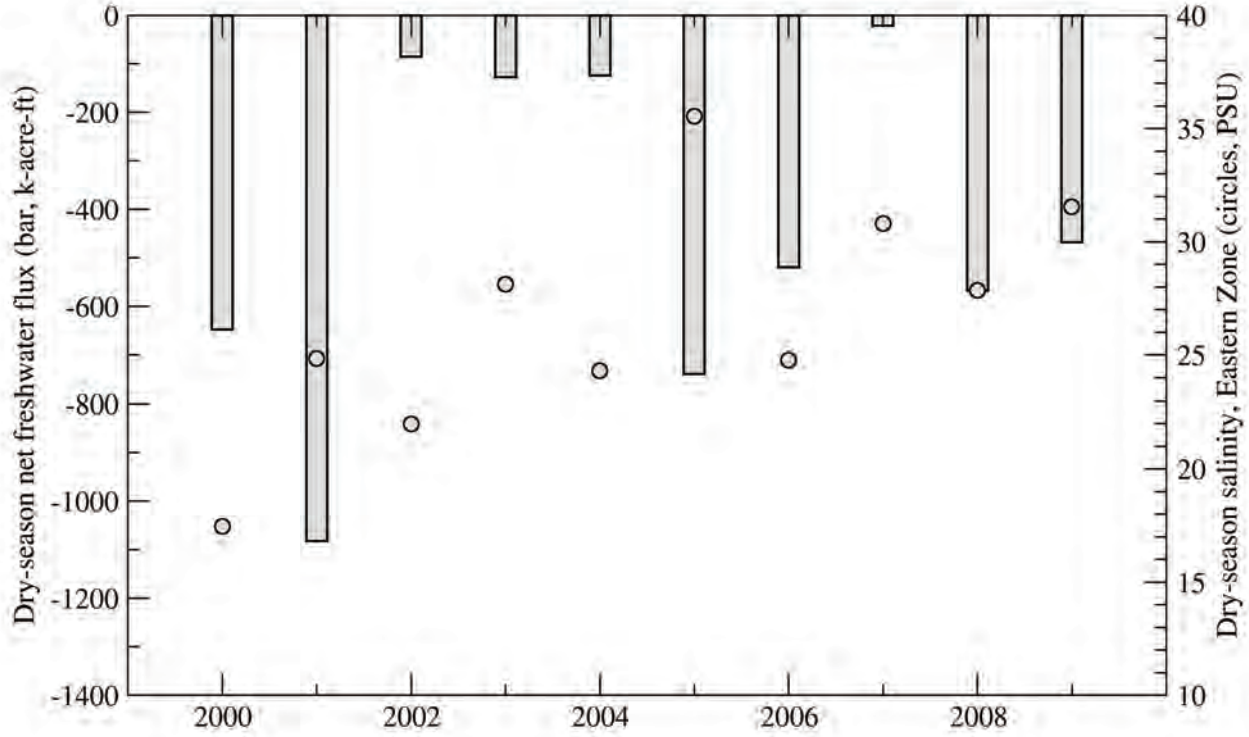

Figure 23. Average dry-season freshwater flux for 2000–2010 showing high variability that is not directly correlated with the apparent trend in salinity.

biological attenuation, where increased resistance to transfer is related to increased density of seagrass beds on the banks themselves. A multiple-decade shift in seagrass species distribution toward more dense monocultures of *Thalassia testudinum* was observed in Florida Bay until the late 1980s, prior to a bay-wide seagrass die-off event (Fourqurean and Robblee, 1999). Subsequent to that event, seagrass populations have rebounded and the vegetation may increasingly be acting as a barrier to transport between basins both by its presence and by stabilizing sediments and providing for increases in bank height. If so, then the trend may subside once changes in the seagrass population stabilize. Additional work using existing datasets and box or hydrodynamic modeling may help to elucidate the cause and expected magnitude of changes in dry-season salinity in Florida Bay.

A bay-wide freshwater budget was developed to predict salinity on a monthly basis (Fig. 24) in order to understand the relative importance of the factors affecting salinity in Florida Bay. The freshwater budget appears to be low by approximately 176 kaf/year (Fig. 24), resulting in a predicted salinity value that is higher than the observed salinity. The missing freshwater component is apparent as an increase in predicted relative to observed salinity only during the dry season. For comparison, a volumetric study of the eastern Florida Bay water budget by Lee et al. (2008) found a missing component on the order of 25–50 kaf/year for that region of the bay. They concluded that this component was likely a groundwater sink. This net loss of Florida Bay water into the groundwater system wouldn't be expected to significantly impact salinity. In the current study, the water budget and differences between the calculated and observed salinity is based on gains and losses of freshwater components. Because there is an impact on the salinity prediction in the dry season, it is likely that evaporation, the dominant feature of the water budget in the dry season and the one feature of the water budget that is not being directly measured in the bay, is overestimated in the freshwater budget. Lower evaporation rates than those calculated here could be responsible for the lower-than-expected salinity. Considering that the evaporation estimate was made as a time series proxy from an original study that

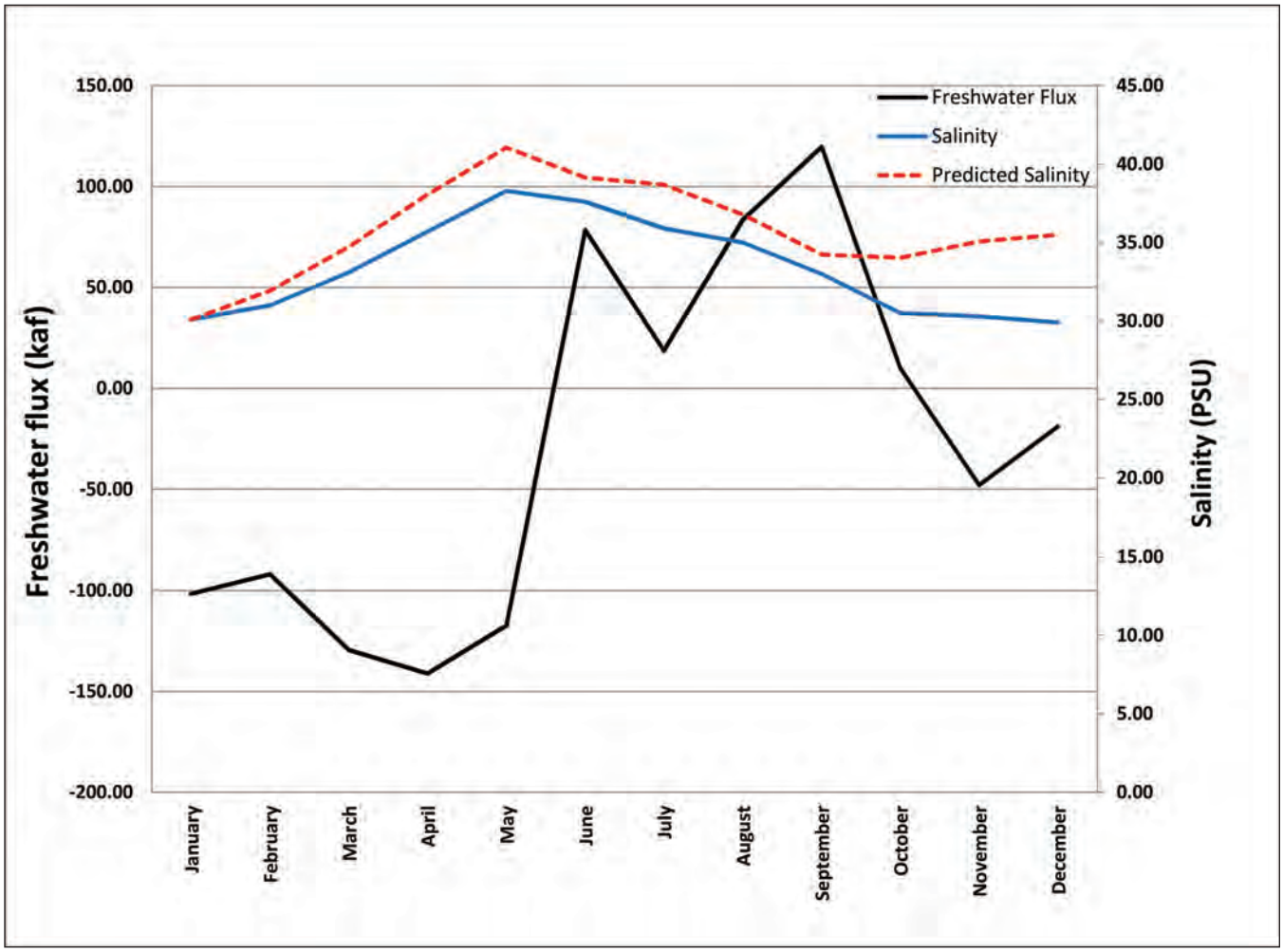

Figure 24. Net monthly freshwater flux was used to predict monthly salinity in Florida Bay. Predicted value deviates from observed values during the dry season and correlates with observed values during the wet season.

had an uncertainty of 10% (Price et al., 2007), it is reasonable that uncertainty in this measurement could account for the missing component. Other likely sources of uncertainty in the water budget that could impact salinity include (1) streamflow measurements include the major creeks but do not include sheetflow or minor creek flow, (2) precipitation is measured at 17 locations and extrapolated across the bay in a uniform manner that wouldn't account for patchiness in the precipitation pattern, (3) brackish or fresh groundwater discharge, and (3) exchange along the western boundary with waters that have a freshwater component derived from Shark Slough.

Sea Level

Sea-level trend analysis was performed on stage data by removing the seasonal components and then applying a simple linear regression on the remainder. Both weekly and monthly aggregate time series analyses were performed using data for several stations representing the western and southern regions of Florida Bay. The selection of stations used in the analysis included stations that had a continuous period of record referenced to a known vertical datum. A seasonal adjustment was made to the weekly time-series by determining the average stage for the period of record for each week of the year and then subtracting that value for the same week of each year in the time series. This method is equivalent to, and allows direct comparison with, the analysis of the greater than 100-year period of record stage data processed for Key West, FL (NOAA Tides and Currents Data, 2010). The results from Florida Bay station LM (Fig. 25) reveal an increase of 0.00846 ± 0.00154 feet/year (2.58 ± 0.47 mm/year), which is slightly higher than the rate of increase observed in Key West (2.24 ± 0.16 mm/year) over the same 16-year period. The total sea-level rise, observed at station LM, was 1.42 inches (36.1 mm) over this period of record or roughly 1 inch (25.4 mm) per decade. Similar trends are observed at other stations within Florida Bay.

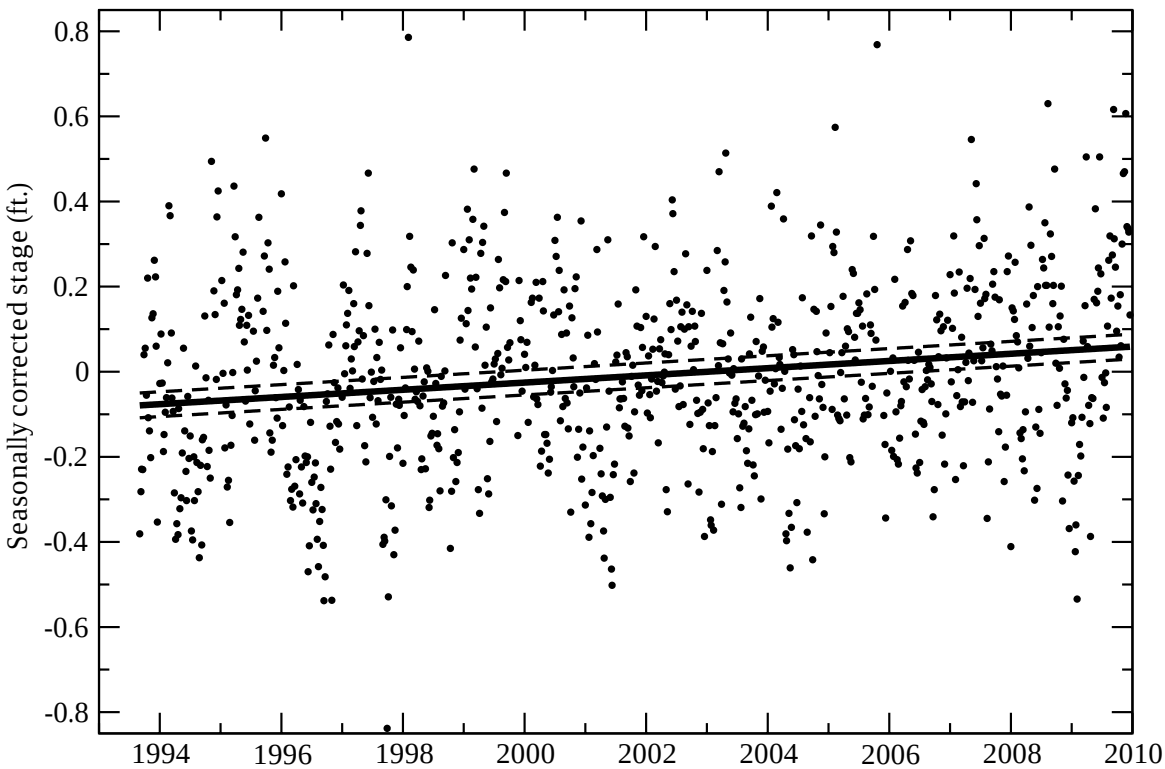

Figure 25. Observations of sea-level rise with 95% confidence interval based on stage data from station LM.

Variability in the sea-level signal in south Florida has been related to variability in several global climate features with results showing that sea level goes through phases of rapid rise followed by relatively stable periods (Karamperidou et al., in press). These cycles operate on periods of 4 and 7 years depending on the interaction between atmospheric drivers over the North Atlantic and sea-surface temperature anomalies in the Pacific. The impact of the variability in the rate of sea-level rise on Florida Bay's shallow water resources is unknown but likely dependent on the balance between accretion and loss on the shallow banks. Differences between the rate of sea-level rise and the accretion rate of the banks can change the connectivity and exchange of water between basins. Changes in connectivity and exchange ultimately affect residence times within basins and salinity in Florida Bay. Continued efforts to understand salinity in Florida Bay should consider the rates involved in both the secular trend and cyclical variability in sea-level rise.

Even a small rise in sea level would affect the size, shape, and other characteristics of the basins in Florida Bay.

Photo by Lori Oberhofer, ENP.

CONCLUSIONS

Everglades National Park staff has engaged in the long-term monitoring of coastal conditions for more than 20 years, yet, even with this abundance of physical data, analysis reveals Florida Bay to be a remarkably complex system. Ultimately, salinity is an ecologically important feature of the bay that acts as an integrator of precipitation, coastal discharge, evaporation, and mixing. The current study indicates that salinity was at its highest value in 1990 at the beginning of the period of record, experienced low values during 1993–1994, and has been increasing since then. The cause of this long-term sequence is unclear; however, it reflects both the net freshwater flux to the bay and mixing of bay waters with the coastal ocean. It remains to be determined if the rise in sea level, which was measured in Florida Bay, is leading to an increase in mixing among basins within Florida Bay, and between the bay and the coastal ocean. Increased mixing would lead to more marine-like conditions within the bay. Alternatively, if the seagrass-covered banks rise at a similar rate to sea-level rise, the result would be a maintaining of the current conditions with respect to mixing. Ultimately, understanding mixing is necessary to understand the bay's freshwater budget and to determine the most effective restoration options to meet coastal salinity targets.

Knowledge about Florida Bay comes from the long-term collection of physical environmental data. The current report is part of an ongoing effort to provide analysis and summaries from these data about conditions in the bay in support of management efforts, restoration projects, and fundamental research. Resource management at Everglades National Park is based on protecting the ecosystem and providing for the most resilient habitat as possible given the regional freshwater constraints. Selecting appropriate restoration efforts requires an in-depth understanding of the response of the physical system, with emphasis on the salinity regime, to various restoration alternatives and then implementing the most appropriate solution. Ongoing monitoring is needed to improve understanding of the system, to make predictions about restoration outcomes, and to confirm the system's response to upstream restoration efforts.

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Sunset over Sandy Key in Florida Bay.
Photo by William Perry.

APPENDIX: Florida Bay monitoring network station information.

Station	Latitude (NAD83)	Longitude (NAD83)	Start date
BA	25.02663	-80.68137	8/9/1993
BK	25.11940	-80.83389	8/9/1993
BN	25.08668	-80.51904	2/8/1990
BS	25.17834	-80.43838	9/11/1991
DK	25.18009	-80.49001	7/14/1988
GB	25.17023	-80.79667	3/6/1996
HC	25.25416	-80.44427	7/14/1988
JB	25.22451	-80.54101	7/29/1993
JK	25.05039	-80.90438	3/13/1989
LB	25.21434	-80.43221	9/11/1991
LM	25.17384	-80.63222	8/25/1988
LR	24.98158	-80.82570	9/11/1997
LS	25.23516	-80.45680	7/14/1988
MB	25.23945	-80.42179	7/11/1991
MD	25.28932	-80.39642	11/21/1991
MK	25.10426	-80.94224	9/4/1997
PK	24.91663	-80.74611	1/24/1989
TB	25.15523	-80.72500	9/12/1991
TC	25.21275	-80.53339	7/14/1988
TP	25.20338	-80.37232	11/21/1991
TR	25.22300	-80.65306	7/14/1988
WB	25.07662	-80.72750	4/6/1989
TRE	25.19083	-80.63917	10/8/1995
SWC	25.22806	-80.48667	4/28/1999
HCE	25.24444	-80.44111	8/9/2001
HCW	25.24222	-80.44750	2/17/1996
ECR	25.19778	-80.61917	5/18/2006
MUD	25.20333	-80.58417	10/15/1995
TROUT	25.21472	-80.53361	2/1/1996
E146	25.25252	-80.66626	3/24/1994
RPL	25.38673	-80.59355	5/1/1949
TSB	25.40292	-80.60732	8/16/1960

L: Limited – Data available from listed start date through mid-2006.

APPENDIX: Florida Bay monitoring network station information—Continued.

Station	Salinity (PSU)	Water temperature (°C)	Discharge (cubic feet per second)	Precipitation (inches)	Stage (feet, NGVD29)
BA	X	X		X	X
BK	X	X		X	X
BN	X	X		X	X
BS	X	X		X	X
DK	X	X		X	X
GB	X	X		X	X
HC	X	X		X	X
JB	X	X		X	X
JK	X	X		X	X
LB	X	X		X	X
LM	X	X		X	X
LR	X	X		X	X
LS	X	X		X	X
MB	X	X		X	X
MD	X	X		X	X
MK	X	X		X	X
PK	X	X		X	X
TB	X	X		X	X
TC	X	X		X	X
TP	X	X		X	X
TR	X	X		X	X
WB	X	X		X	X
TRE		L	X		
SWC		L	X		
HCE		L	X		
HCW		L	X		
ECR			X		
MUD		L	X		
TROUT		L	X		
E146	X	X		X	X
RPL				X	
TSB				X	X

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