Physical Processes

How and at what rates do storms, changing fresh water flows, sea level rise, and local evaporation/precipitation patterns influence circulation and salinity patterns within Florida Bay and exchanges between the Bay and adjacent waters?

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About this report

This report draws its material directly from syntheses compiled for the 2001 Florida Bay Science Conference. The Florida Bay Science Program organizes itself around five central research questions. Topical teams associated with each question consist of modelers and researchers working in the Bay and adjacent marine systems. These teams compiled the original synthesis documents.

In preparation for the 2003 Florida Bay Science Conference, the research teams have modified the existing synthesis documents to bring them up to date and implement a uniform, common format. In some cases, entirely new documents have been drafted, such as the information here on ecosystem history and on nutrient dynamics. The present report compiles these separate documents into one and provides the reader with summary material as a guide to the contents.

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Introduction

Question 1: How and at what rates do storms, changing fresh water flows, sea level rise, and local evaporation/precipitation patterns influence circulation and salinity patterns within Florida Bay and exchanges between the Bay and adjacent waters?

The research conducted addressing Question 1 is intended to lead to quantitative prediction of the responses of circulation and salinity within Florida Bay and its exchange with the Gulf of Mexico and the coastal zone of the Florida Keys to oceanographic, climatic and hydrological driving processes. Table 4.1 includes relevant representative references to research addressing driving forces, system characteristics and their intersection. Research Summary highlights the major findings to date.

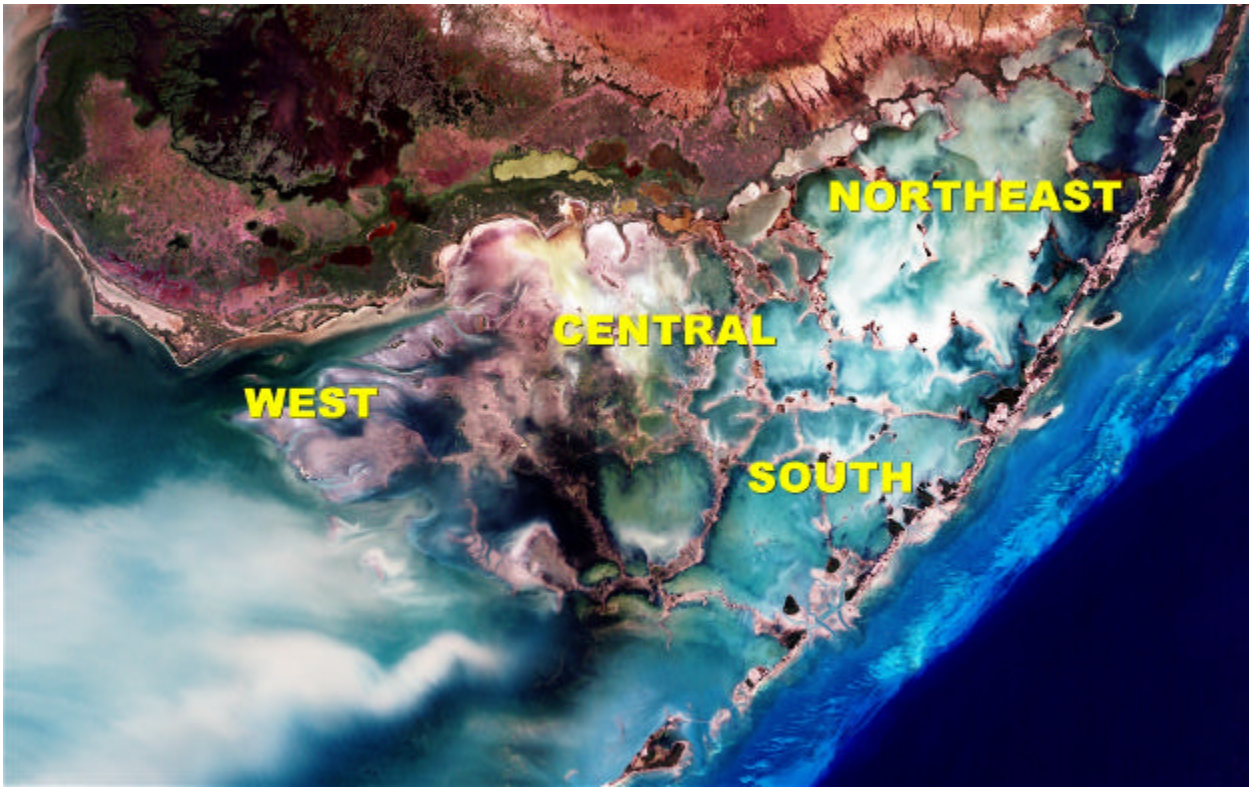
Background

The south Florida coastal system surrounding and interacting with the interior waters of Florida Bay, made up of the Gulf and Atlantic waters of the Florida Keys, the Dry Tortugas, and the southwest Florida shelf, is found to be highly coupled by the combined influence of coastal and oceanic currents (Lee et al., 2001a). The Bay itself is a lagoonal system with a complex network of shallow, often intertidal, banks isolating the interior portions of Florida Bay from the direct influence of regional or larger scale oceanographic processes, Figure 4.1. As a result, local and direct climatic processes such as the inflows of surface and groundwater, rainfall, evaporation, and wind-driven flow exert large effects on salinity, circulation, and exchange processes.

The climate of south Florida is subtropical with a comparatively small annual temperature range but distinct wet (summer/fall) and dry (winter/spring) seasons. During the wet season, showers occur virtually daily with the afternoon sea breeze, and tropical storms are transient occurrences. During the dry season, cold fronts pass through the region on an approximately weekly basis with accompanying increased wind speeds and clockwise rotating wind directions.

Spatially, the Bay can be thought of as four distinct regions subject to different geophysical forcing, topographic constraints, and fresh water inputs. The northeastern region of Florida Bay is not significantly affected by tides or directly influenced by the surrounding marine waters of the Atlantic and Gulf of Mexico. This region is the direct recipient of fresh water flows from the Taylor Slough and the C-111 canal system. Upstream water management practices influence the quantity, timing and distribution of fresh water entering this region. Runoff varies spatially across the northern boundary, with the greatest flow through Trout Creek. Wind events often determine the timing of fresh water discharges on hourly to daily time scales, and regional rainfall cycles (e.g. seasonal and El Nino/La Nina driven) influence discharges on annual to multiyear time scales. Salinity along the northern boundary of the Bay responds very rapidly to rainfall and/or discharge events. High flow causes dramatic freshening in the small bays along the northern boundary. Subsequently, fresh water slowly mixes with more saline Florida Bay waters to the south and southwest over a period of weeks to months (Johns et al., 2001a).

Figure 4.1: LANDSAT-7 extended thematic mapper image of Florida Bay, showing its shallow bank bathymetry and four principal subregions.



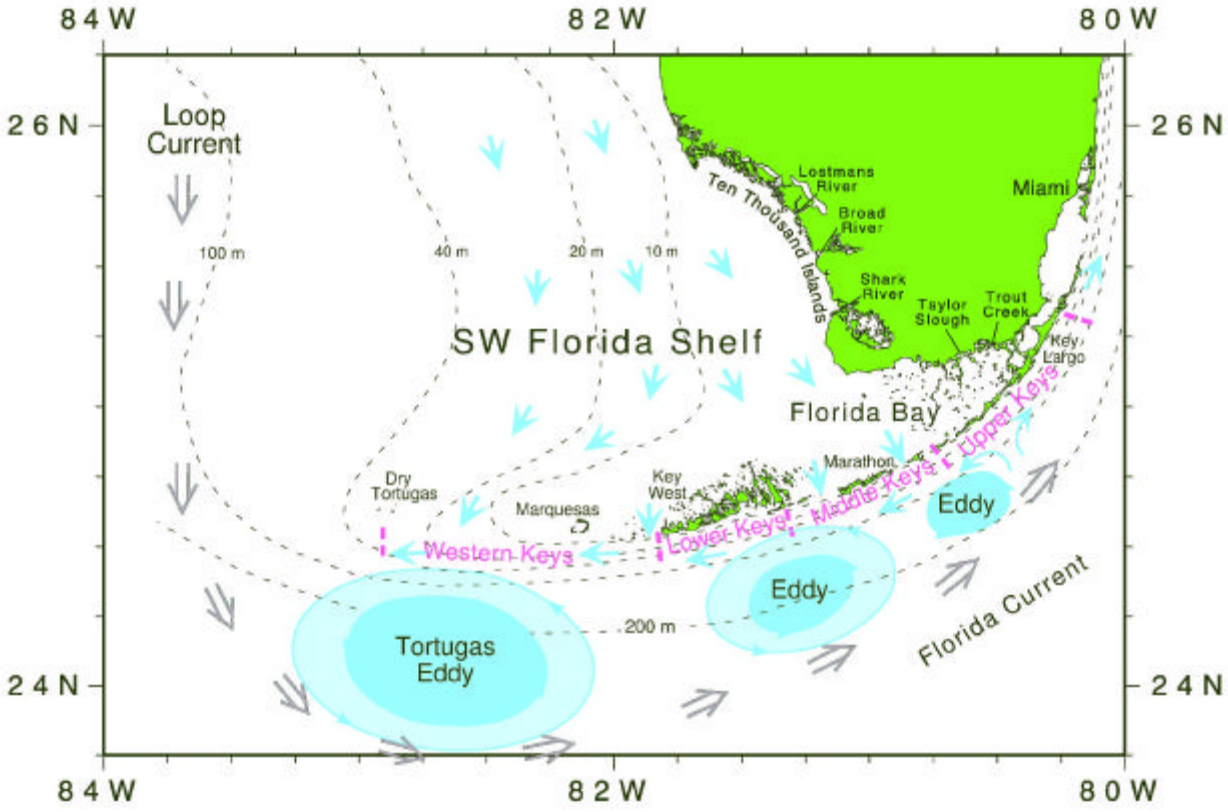
The central region of Florida Bay receives less direct fresh water inflow, but fresh water can move into central Florida Bay through McCormick Creek into Terrapin Bay, and through Alligator Creek into Garfield Bight, as well as over the Buttonwood Embankment. Groundwater inputs have also been hypothesized. Under historically higher water levels, throughout the southern Everglades these surface and groundwater inputs were presumably more significant. During times of reduced precipitation and high evaporation this central area can become hypersaline with salinity often in excess of 40, and historically as high as 70 (Boyer and Jones, 2001; Robblee et al., 2001). High salinity persists over periods of weeks to months, indicating that, like the northeastern region, waters of the central region have a relatively long residence time.

The western region of Florida Bay is the least topographically isolated, sharing an open boundary with the Gulf of Mexico, and exchanging water with the central region of Florida Bay through the main Flamingo channel and the Atlantic Ocean through passages in the middle Keys. This western region is also subject to robust tidal mixing. Residence times in the western region are therefore shorter than in the central and northeastern regions, and salinity can exhibit a relatively rapid response to meteorological events such as tropical storms and cold fronts. Oceanographically, the entire coastal system of south Florida is one integrated system (Fig. 4.2). Florida Bay is connected to the southwest Florida shelf, and on occasion to more remote regions of the Gulf of Mexico. As a result, western Florida Bay can be influenced by the delivery of fresh water from rivers discharging in the Ten Thousand Islands region and along the west coast of Florida (the Shark, Broad, Harney, and Lostmans rivers). These river waters are carried southward along the southwest Florida coastline and around Cape Sable, in a general pattern of outflow through the Keys to the reef tract (Lee et al., 2001a; 2001b). The influence of fresh water inflow from remote Gulf regions is more likely during summer and fall, and has been shown to include the influence of Mississippi River floods (Ortner et al., 1995). Subsequent transport of this water to Florida Bay and the Keys is aided by oceanic flows, the Loop Current and the Florida Current.

Finally, the south region of Florida Bay differs from the central region in that it has an open connection through the middle Keys passages, and at times can alternatively be affected by the influence of Atlantic ocean water, or can be a source of Bay waters to the coral reef areas of the Florida Keys National Marine Sanctuary (FKNMS).

Circulation of water in western Florida Bay and adjacent coastal regions on subtidal time scales is strongly influenced by local wind forcing that results in seasonal flow patterns: southward toward the Keys in winter and spring, northwestward into the Gulf in summer, and southwestward toward the Tortugas in the fall. Episodic transport processes deliver warm, salty water to the reef tract from Florida Bay in the spring and early summer. Cold, turbid intrusions can occur in the winter.

Figure 4.2: Schematic representation of the average flow patterns in the interconnected South Florida coastal circulation system. The single arrows represent mean current directions while the double arrows represent the Loop Current and the Florida Current.



Research Summary

Researchers to date have documented regional driving processes, circulation in the outer portion of Florida Bay and the adjacent southwest shelf and Florida Keys, exchange between Florida Bay and the Keys coastal zone, the potential pathway for exchange across the western boundary, and the patterns of salinity variation throughout the Bay and the adjacent marine systems. These results derive from several extensive observational programs that have now collected almost ten years of data on regional water properties, meteorology, and flow.

By comparison, major uncertainties remain about circulation within the interior basins, inter-basin exchange, flow across the bank tops, the effect of evaporative processes upon bank top waters, groundwater entering the Bay across its northern boundary and the quantitative details of exchange across the Bay's extensive and complex western boundary. Moreover, while the hydrological model of surface waters entering northeast Florida Bay has been improved over the last few years and progress has been made on expanding this to the entire northern boundary and the lower southwest shelf including the Shark River slough, at present we still do not have an adequate hydrodynamic model of the interior of Florida Bay.

As a result, our ability to rigorously forecast changes in salinity within the Bay resulting from planned modifications in upstream water management is not adequate. However, a water budget has been developed for Florida Bay based upon a long term (31 years) salinity data set that takes into account seasonal and interannual variations in the supply of fresh water (Nuttle et al., 2000). A depiction of the climatic cycle of surface runoff, evaporation and precipitation over the 31-year period is shown in Fig. 4.3. Across the whole Bay, discharge from the estuarine creeks amounts to about 2 cm/year, or about 20 percent of the annual rainfall. In the northeast region, where the majority (98 percent) of the creek discharge enters the Bay, creek discharge amounts to about 67 percent of the annual rainfall. At present, similarly to the 31-year average, the majority of the fresh water inflow is concentrated in the northeastern part of the Bay and has a major influence on salinity variations therein, effectively inhibiting hypersalinity. Conversely, the lack of fresh water flow to the central Bay exacerbates hypersalinity.

Higher discharges through the Shark River slough and higher water levels in the southern Everglades could redistribute fresh water input into the Bay and could in particular provide greater input to the central basins. Integrated hydrological/hydrodynamic models incorporating the most recent observational data and process study results and linked to appropriate regional/boundary hydrodynamic and atmospheric models are required to rigorously address the most central management concern: what salinity distributions will result from various upstream water management alternatives. This has become a principal objective of the Florida Bay/Florida Keys Feasibility study.

The principal findings are summarized below and relevant citations are enumerated in Table 4.1:

Table 4.1: Research topics defined by Question 1 and representative references to relevant research

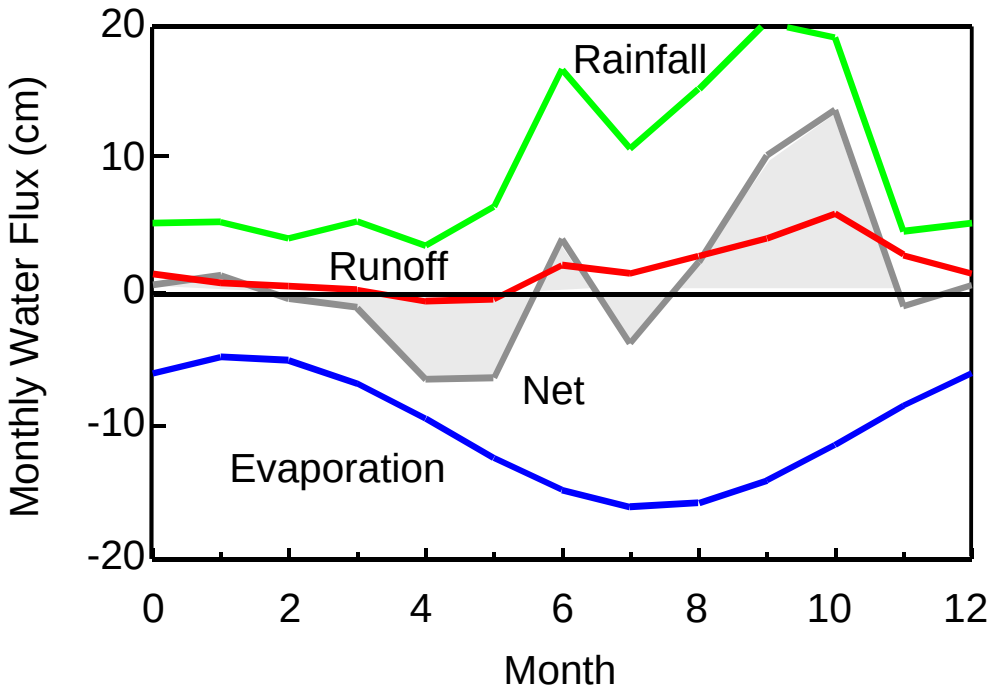
	ECOSYSTEM CHARACTERISTICS		
DRIVING PROCESSES	**Salinity Patterns** Robblee et al. (2001), Boyer et al. (1997), Boyer and Jones (2001), Lee et al. (2001), Johns et al. (2001a), D. Smith (2001)	**Circulation Patterns** Lee and Williams (1999), Lee et al. (1999), Lee et al. (2001a), D. Smith (2001)	**Exchanges with Adjacent Waters** N. Smith (2002), Smith and Pitts (2001), Lee and Smith (2002), Yang (1999), Lee and Williams (1999), Lee et al. (1999), Lee et al. (2001a)
Winds and Storms Goldenberg et al. (2001), Mattocks (2001), Chen et al. (2001)	Johns et al. (2001b), D. Smith (2001), R. Smith et al. (2001)	Lee and Williams (1999), Lee et al. (2001a), Smith and Pitts (2001), Wang et al. (1994), N. Smith (2001)	Lee and Smith (2002), Smith and Pitts (2001), N. Smith (2001), Johns et al. (2001b)
Precipitation Willis (2001), Trimble et al. (2001), Mattocks (2001), Pielke et al. (1999), Swart and Price (2001)	Swart and Price (2001), Nuttle et al. (2000, 2001), Johns et al. (2001a)	No observed effect of precipitation on circulation has been reported.	No observed effect of precipitation on exchanges with adjacent waters has been reported.
Evaporation Pratt and Smith (1999), N. Smith (2000), Price et al. (2001), Mattocks (2001), Nuttle et al. (2000, 2001)	Swart and Price (2001), Nuttle et al. (2000, 2001)	No observed effect of evaporation on circulation has been reported.	No observed effect of evaporation on exchanges with adjacent waters has been reported.
Surface Water Nuttle et al. (2000), Hittle et al. (2001), Vosburg et al. (2001), Cable et al. (2001), Swart and Price (2001), Levesque and Patino (2001), Trimble (2001)	Lee et al. (2001a), Ortner et al. (1995), Hurricane Georges Workshop, Nuttle et al. (2000, 2001), Swart and Price (2001), Johns et al. (2001a), Langevin et al. (2002a), Schaffranek et al. (2002)	Lee et al. (2001a), Langevin et al. (2002a)	No observed effect of surface water on exchanges with adjacent waters has been reported.
Groundwater Price and Swart (2001), Fitterman et al. (1999), Fitterman and Deszcz-Pan (2000, 2002), Langevin et al. (2002a), Vosburg et al. (2001), Top et al. (2001)	Fitterman et al. (1999), Fitterman and Deszcz-Pan (2001), Langevin et al. (2002a)	Langevin et al. (2002a)	No observed effect of groundwater on exchanges with adjacent waters has been reported.
Sea Level and Tides Wang et al. (1994), Maul and Martin (1993), N. Smith (1997), Frederick et al. (1994)	Lee et al. (2001a, 2001b), Johns et al. (2001a)	Lee and Smith (2002), N. Smith (1998), Wang et al. (1994)	N. Smith (1998), Smith and Lee (2001), Lee and Smith (2001), Smith and Pitts (2001), N. Smith (2001)
Boundary Currents Lee et al. (2001a, 2001b), Lee and Williams (1999), Lee and Smith (2002), Yang et al. (1999)	Ortner et al. (1995), Lee et al. (2001a, 2001b)	Lee et al. (2001a), Yang et al. (1999)	Lee et al. (2001a, 2001b), Yang et al. (1999)
PREDICTION	Nuttle et al. (2000, 2001), Cosby et al. (1999), Wang, Marshall (2001), Walker (1998), Kim et al. (1999)	Wang et al. (1994), Kim et al. (1999)	HYCOM model group

SALINITY

- Historical salinity data and salinity proxy data show that Florida Bay salinity has commonly undergone large salinity changes on time scales of seasonal, interannual (ENSO, the El Nino-Southern Oscillation), decadal (NAO, the North Atlantic Oscillation), and even longer periods that are not yet understood.

- Historical data from the salinity synthesis database (Robblee et al., 2001) show that Florida Bay has behaved as a marine lagoon for the past several decades with salinity reaching as high as 70 in the central Bay on a few occasions, and typically exceeding 40 during drought years like 1989-90. For example, following the wet period of 1994-1995 salinity increased, tropical storms in 1999 induced a decrease, and data from the drought years of 2000 and 2001 indicated a further increase. More recent data from 2002 and early 2003 indicate another general freshening trend.
- Variability of Florida Bay average salinity is directly related to the net flux of fresh water from the combined influence of evaporation, precipitation, and runoff. For the Bay as a whole, on seasonal or annual time scales, evaporation is approximately equal to precipitation, while runoff is roughly twenty percent of either.
- Recent studies have narrowed the range of evaporation to around 75-180 cm/year.
- Shallow bank configurations, which restrict water exchange, tend to separate the Bay's interior into three distinct regions with differing salinity variations. The northeast basin is the most isolated from oceanic influences, receives most of the surface runoff and has the largest seasonal cycle of salinity; the central basin receives little runoff and has the maximum salinity; and the western basins have the greatest oceanic exchange and the smallest seasonal change in salinity.
- Continuous surveys of the Bay's salinity patterns show large spatial gradients coinciding with wide, shallow bank structures that tend to inhibit inter-basin exchanges.

Figure 4.3: Average seasonal rainfall, runoff, evaporation and net fresh water gain/loss in Florida Bay (Nuttle, pers. comm.).



FRESH WATER INPUT

- Stable isotopic markers indicate that the dominant source of fresh water for northeast Florida Bay is Everglades runoff, whereas for the western region precipitation shows a stronger signal. In the central region, a mixture of runoff and precipitation provides the fresh water.
- Measurement and modeling (both hydraulic and regression) of surface inflows to the Bay from the Everglades continues to improve. These analyses show that there have been increasing inflows to Taylor Slough and the C-111 canal since 1985 due to management activity.
- Trout Creek contributes the largest volume of fresh water to northeast Florida Bay, varying from -6 to 32 m^3/s. By contrast, the flow from each of the other eight creeks ranges from -1.4 to 6 m^3/s. Negative flows can occur during the dry season and from storm events.
- For the Ten Thousand Island region of the western Everglades, the mean annual river discharge is estimated at 13.3 m^3/s for Harney River, 11.0 m^3/s for Broad River, and 12.4 m3/s for Shark River.
- Low salinity Shark River plume waters are commonly advected southward around Cape Sable to western Florida Bay and the Keys reef tract by wind-driven coastal flows.
- Groundwater inflows are believed to be most influential along the northern boundary of the Bay; however, estimates of the volume of this flow range over four orders of magnitude. New measurements and hydraulic modeling should help to put bounds on the inflow estimates.

CIRCULATION AND EXCHANGE

- The entire south Florida coastal system, consisting of the southwest Florida shelf, the Florida Keys reef tract, and western Florida Bay, is highly connected by local and oceanic circulation patterns responding to wind and boundary current forcing.
- Large volume wind-forced flows through the Keys passages provide linkage for Gulf to Atlantic exchange through the open western region of Florida Bay.
- Measurement of sea level slopes across the Florida Keys provides a tool for monitoring Gulf-to-Atlantic transports toward the reef tract of heat, salt, nutrients or toxic algae.
- Seasonal cycles in local wind forcing produce seasonal patterns in circulation pathways, connecting south Florida coastal waters through western Florida Bay and transporting Everglades fresh water discharges. Southward flows through the Keys passages predominate in winter and spring, north-northwest flows in summer, and southwest flow toward the Tortugas in the fall.
- Seasonal cycles in south Florida coastal current systems provide seasonal pathways for local larval recruitment and opportunities for recruitment from remote sources.

- The south Florida coastal region is surrounded by an intense, large-scale oceanic boundary current (the Loop Current/Florida Current system) and its evolving eddies that link local coastal waters to remote upstream river sources in the Gulf of Mexico.

PREDICTION

Although still not available as a management tool, steady progress has been made toward developing a predictive capability for salinity and circulation changes in Florida Bay and connecting coastal waters as follows:

- 2-D hydrodynamic models with coarse grids have been developed for Florida Bay as pilot projects by J. Wang (finite element) and J. Hammerick (finite difference) that show encouraging salinity pattern results similar to observations.
- Better estimates of surface and groundwater inflows are available from recent measurements and hydraulic model results of the United States Geological Survey (USGS) and the South Florida Water management District (SFWMD).
- Improved estimates of evaporation are available from recent studies of R. Price, P. Swart, W. Nuttle, and N. Smith.
- Improved estimates of precipitation patterns and quantities are available from calibrated NEXRAD measurements (P. Willis).
- Measurement of interior basin circulation and exchange processes are available to improve understanding of Bay dynamics, quantify residence times and help validate and improve hydrodynamic models (T. Lee, E. Johns, V. Kourafalou, and N. Smith).
- Modeling Terms of Reference were established by the Physical Science Team (PST) and approved by the Program Management Committee (PMC).
- A Standard Data Set has been established for model use (J. Pica).
- An interagency nested model program has been formulated using regional hydrodynamic and hydrological models to provide boundary conditions for the Florida Bay model (SFWMD, USGS, and the National Oceanic and Atmospheric Administration, NOAA).

Driving Processes

Winds and Storms

Winds in south Florida including Florida Bay follow a regular seasonal pattern: weak southeast winds and daily sea breezes in summer, persistent northeast winds in fall, and the regular passage of cold fronts causing moderate increases in wind speed and a clockwise rotation of wind direction in winter. During hurricane season (summer/early fall) the persistent southeast tradewind and sea breeze pattern can be interrupted by the passage of tropical storms with a frequency of one per 1-2 years resulting in substantial increases in wind speed, precipitation and runoff, which can inflow directly to the central basin. Due to the absence of significant topography in south Florida winds overall are highly coherent across the Bay, with the exception of locally intense convective events. Low frequency wind stress varies seasonally (N. Smith, 2002). Since low-frequency scatter about the monthly mean is an important measure of wind forcing, this seasonal variability is significant.

Recent measurements indicate that there is a significant response of the salinity patterns, sea level, currents and turbidity of Florida Bay and adjacent coastal waters to wind forcing associated with the passage of even relatively weak tropical cyclones (Johns et al., 2001b; Hurricane Georges Workshop report). Based on several research efforts at different locations, the effect of storms on water levels in the Everglades and in Florida Bay, and the fresh water flow response after storms pass, has been characterized (D. Smith, 2001; Johns et al., 2001b; R. Smith et al., 2001).

Studies by Mattocks (2001) using a version of the Advanced Regional Prediction System (ARPS) mesoscale atmospheric weather prediction model reconfigured to match South Florida Water Management District (SFWMD) models at a 3.2 km resolution and including land use and soil types, show mesoscale structures in wind, evaporation and precipitation fields that are associated with land use and land/sea interactions including sea breeze. Strong divergent downdraft outflows that occur beneath thunderstorms and over the Florida Keys appear to produce their own sea breeze convergence fronts. The different soil types and land uses, together with the spatial patterns in the wind fields, determine spatial patterns in the evaporation and precipitation fields over south Florida and the surrounding waters including Florida Bay.

Indications are that we are entering a period of enhanced Atlantic hurricane activity (Goldenberg et al., 2001) and that the prior two or three decades represented a period of diminished activity. The difference apparently reflects a multi-decadal climatic oscillation. If the assumption is made that the probability of a tropical storm affecting south Florida is directly related to overall activity, this implies that Florida Bay is more likely to be affected by a storm than has been the case for the previous several decades. The authors suggest that this pattern is likely to continue for an additional 10 to 40 years.

Precipitation

South Florida in general, including Florida Bay, has a pronounced dry season (winter/spring) and wet season (summer/fall). Nuttle et al. (2000) used 31 years of historical data to show that the seasonal rainfall pattern for the Bay as a whole is nearly balanced by Bay-wide evaporation. The distribution of rainfall is highly heterogeneous due to the dominance of local convective events and sea breeze convergences, and to variations caused by urban development effects known as

"desertification" (Pielke et al., 1999). Significant climatic variability is however possible, and has been documented within the period of record of the ongoing monitoring.

Trimble et al. (2001) have indicated that low frequency meteorological modes associated with ENSO and the Pacific Decadal Oscillation can also have significant effects on south Florida rainfall and fresh water supply variability. For example, Johns et al. (2001a) have shown that the El Nino of 1998 reversed the seasonal rainfall pattern over south Florida, causing a winter/spring wet season and a summer/fall dry season.

There is excellent agreement between independent data set tests using NEXRAD radar and rain gauges (Willis, 2001). Cumulative rainfall distributions are nearly identical except for the highest rainfall rates. Radar estimated rainfall distributions provide the high resolution needed to resolve spatial patterns over south Florida and Florida Bay. This NEXRAD precipitation product, done on a research basis for two years, has now been mapped to the SFWMD grid and is archived at SFWMD. These efforts have paved the way for an operational rainfall distribution product that can be input to atmospheric models.

Evaporation

Evaporation in marine systems is a function of air and water temperature difference, specific humidity and wind speed. Although winds are highly coherent across the Bay, ongoing studies suggest that there are significant spatial differences in evaporation minus precipitation (E-P) (Price et al., 2001). Recent estimates of evaporation in Florida Bay have employed a variety of independent methods and the comparison of results is encouraging. For example, an analysis was conducted from data obtained at three stations across northern Florida Bay for the period March 1996 to April 1997 (Pratt and Smith, 1999). Each station recorded wind speed, wind direction, air temperature, air pressure, relative humidity, rainfall, incoming solar radiation and evaporation losses with evaporation pans. (Surface water temperature was not measured and had to be estimated from other measurements, causing a source of error in the analysis.)

Nuttle et al. (2000, 2001) also estimated Bay-wide annual evaporation, based on calibration of steady state box models using historical salinity data for each of four regions in the Bay, to be 110 cm. Pratt and Smith (1999) estimated annual evaporation to be 73 cm by using a Dalton Law formula. Subsequent to this study, N. Smith (2000) refined the application of the Dalton Law approach by including the effect of increasing estimated annual evaporation. On the other hand, estimates based on surrogate data differ by up to a factor of three. Evaporation pan data are available for several years from Flamingo, from a site located on the north shore of the Bay. The average of these data is 210 cm/year (National Climatic Data Center), which appears to be too high to accept directly as an estimate of evaporation in the Bay.

A distinct seasonal cycle underlies the annual mean water loss, with a maximum in late summer and a minimum in mid winter. Calculations using the Long Key C-MAN data in bulk aerodynamic formulas indicate average evaporative water losses of approximately 0.7 cm/day in September and October, and approximately 0.3 cm/day in December and January. Unpublished data from this 15-month study (N. Smith, pers. comm.) indicate a mean daily evaporative water loss of 0.5 cm and a total annual water loss of approximately 180 cm. Therefore, reliable evaporation estimates appear to be converging upon the 75-180 cm/year range, but more research is required to confirm this amount.

Surface Water Input

A significant amount of surface water directly enters Florida Bay only along its northern boundary with the southern Everglades and is concentrated at present in the northeast region. Fresh water does on occasion enter the central Bay directly if there is enough rain, as occurred during and after Hurricane Irene when there is evidence that fresh water from the Everglades was able to flow over the Buttonwood Embankment, for example (Johns et al., 2001a).

Fresh water runoff enters primarily through natural channels cut through the mangrove and buttonwood confining berms (Hittle, 2001; Hittle et al., 2001). USGS measurements indicate that Trout Creek contributes the largest annual discharge of fresh water into northeast Florida Bay, varying from between about 110,000 to 190,000 acre-ft per year (4.3 m^3/s to 7.4 m^3/s). By contrast, the annual discharge from each of the other eight creeks varies between 10,000 and 45,000 acre-ft per year (0.4 m^3/s to 1.8 m^3/s). Negative flows over the mangrove embankments can be caused by storm events, and net negative monthly average flow, usually lasting for several months, occurs in all creeks during every dry season represented by the data.

Cable et al. (2001) have reported on the relationship between precipitation and inflow into Florida Bay, finding that fall and winter storms cause pulse fresh water inflow events, with the flow in Taylor Creek showing a marked response to the storms. Typically, water levels in the Everglades were found to be highest in early fall and lower in the winter. Tropical storms cause the water level in the Everglades and Taylor Slough to rise relatively rapidly, and then recede slowly after the storms pass. The water level rise is on the order of hours, while the fall is on the order of weeks. In winter, northeasters drive water out of Taylor Creek into Florida Bay.

Stable isotopic markers have identified the principal sources of fresh water in various regions of the Bay (Swart and Price, 2001). Fresh water inputs to northeast Florida Bay are dominated by contributions from Everglades runoff. Rainfall has a strong signal in the west; and both rainfall and runoff provide fresh water to the central portion of the Bay.

Fresh surface water inputs from the rivers of the southwest coast of Florida (primarily the Broad, Harney, and Shark rivers) may also be significant to Florida Bay, particularly in its western region. Levesque and Patino (2001) report measurements of water level, velocity, specific conductance, and temperature in each of these three rivers during calendar year 1999. Discharges from the three rivers are influenced by the semi-diurnal tides, wind, and fresh water flows from the watershed. All three rivers are well mixed, with very little vertical gradient except near the coastal front. The only evidence of stratified, bi-directional flow is around the time of slack tide conditions. Instantaneous discharges ranged from –2,400 to +3,500 cfs (-68 to +99 m^3/s) in the Broad River, -15,600 to +12,900 cfs (-442 to +365 m^3/s) in the Harney River, and –10,100 to +10,500 (-286 to +247 m^3/s) for the Shark River. When tidal effects have been filtered from the data, the residual flows ranged from –900 to +2,500 cfs (-25 to +71 m^3/s), -3,600 to +5,700 cfs (-102 to 161 m^3/s), and –2,300 to +4,400 cfs (-65 to +124 m^3/s) for the Broad, Harney, and Shark Rivers, respectively. Mean annual residual discharge values are reported at 400 cfs (11 m^3/s or 284,000 acre ft/year) for Broad River, 440 cfs (12.4 m^3/s or 320,000 acre ft/year) for Shark River, and 470 cfs (13.3 m^3/s or 343,000 acre ft/year) for Harney River.

Groundwater Input

Anecdotal/historical information suggests that, prior to water management, groundwater inputs to south Florida estuaries like Biscayne Bay and Florida Bay were significant. At present, because of lowered water tables and the intrusion of seawater into the coastal aquifer, fresh groundwater may be prevented from discharging directly into Florida Bay. However, groundwater may be passing from the Floridan aquifer into the surficial aquifer and then into Florida Bay. Because the Floridan aquifer is saline, the discharging groundwater would be saline, not fresh. This hypothesis is supported by geophysical measurements in the southern portions of Everglades National Park (ENP) between Flamingo and U. S. 1 that indicate that the aquifer is saltwater saturated from the surface at least to a depth of 15 m (Fitterman et al., 1999; Fitterman and Deszcz-Pan, 2000, 2002). Results from the integrated surface/groundwater model of the southern Everglades suggest that groundwater seepage beneath the Buttonwood Embankment may be allowing brackish water from the Everglades to discharge into northeastern Florida Bay (Langevin et al., 2002a). Model results suggest that surface water can be impounded on the north side of the embankment creating a hydraulic drive for groundwater discharge into Florida Bay. Data are lacking, however, to support these model results.

Vosburg et al. (2001) report on surface water and groundwater measurements, which were taken at two locations in the dwarf mangrove wetlands along Taylor Creek near the river mouth at Florida Bay. Water levels of surface water and groundwater were measured at both sites. Surface water levels demonstrated a relatively rapid response to rainfall, runoff, tide, and wind while the groundwater response was less rapid. However, groundwater response times were different at each site, which is attributed by the authors to the difference in sediment type.

Price and Swart (2001) have provided recent additional information about the role of groundwater in the hydrologic regime of Florida Bay and the adjacent areas of the Everglades. The extent of saltwater intrusion into the surficial aquifer increases from east to west, extending about 6 km inland along the C-111 canal basin to about 20-28 km inland at Shark River Slough (Fitterman and Deszcz-Pan, 2000, 2001). Groundwater may be discharged into the overlying surface waters of the Everglades within this strip that more or less parallels the coastline. An empirical calculation of groundwater discharge yields values of about .04-0.175 cm^3/day.

Top and Brand (2001) have also recently studied groundwater in Florida Bay. They used anomalies in the dissolved helium concentrations in groundwater to estimate groundwater inputs into Florida Bay. These authors used a box model to estimate the input of groundwater to Florida Bay at 2.5-4.0 cm/day in the summer and 10-16 cm/day in the winter. Radon data estimates yield a groundwater flux of 0.8-1.7 cm/day. According to these authors, Floridan aquifer saline water that is under artesian pressure is rising through breaks in the confining layer where it is mixed with the shallow aquifer before entering Florida Bay; the two-layer structure of the aquifer system explains the difference between the helium and radon flux estimates.

Note that the radio-isotope values convert to hypothesized groundwater inflows of 575 to 3680 m^3/s. Based on these results, if true, groundwater would appear to be a significant source of saline water to Florida Bay. However, these estimates have large differences and appear to conflict with mass balance water budget estimates and the observed large seasonal salinity variations.

Sea Level and Tides

Sea level variability in Florida Bay is controlled by wind and tidal forcing, strongly modified by topography and coastline (Wang et al., 1994). Regional sea level is thought to have risen rapidly in the last century (Maul and Martin, 1993; see also the Key West sea level record from 1913-present, available from the National Climatic Data Center, NCDC) but the implications of that observation are not addressed herein. Differences in sea level between basins and across tidal passages can be a dominant factor controlling flow and renewal of Bay waters. A mixed tide results from the diurnal tide of the Gulf combined with the semi-diurnal tide of the Atlantic. This results in the largest tidal ranges south of Savannah, Georgia, for the region near the mouth of the Shark River (>2 m at spring tide). Measurements at East Cape indicate a mean tidal range of only 75 cm. The mean range is half that at the southern end of the western boundary, just north of Marathon. However, the tide entering the interior of the Bay is strongly damped by the shoals and mud flats, decreasing the range to just a few cm in the northeast (N. Smith, 1997).

N. Smith (1997) also reports upon spatial patterns of tidal water level fluctuations in the interior portion of Florida Bay and the seasonal pattern of water level fluctuations at subtidal frequencies. Wind set-ups of 10-30 cm are observed inside the Bay but the basin-to-basin variations in wind forcing are not well understood at present. An annual change in sea level of about 30 cm is widespread over the western North Atlantic and extends into the interior of the Bay as well.

Boundary Currents

The Loop Current in the Gulf of Mexico and its extension the Florida Current in the Atlantic, surround the south Florida coastal waters and the Keys. The former is part of the Gulf Stream system, which is one of the strongest and best studied western boundary currents. Both currents are complex and can generate eddies and meanders that can affect how they interact with Florida Bay. Together these oceanic currents cause sea level differences across the Keys that can drive flows through western Florida Bay. Lee and Smith (2002) have recently shown that changes in sea level slopes across the Keys are a direct response to tide and wind forcing, and they have inferred a longer period response to Loop Current extensions into the Gulf of Mexico. Wind forcing affects sea level differently on the Atlantic and Gulf sides of the Keys causing sea level slopes that can enhance the exchanges of Bay waters with the surrounding regions. The boundary currents and their induced flows along western Florida Bay can transport river waters and/or algal blooms from remote regions to interact with the Bay (Lee et al., 2001a, 2001b).

Influence of Driving Processes

Salinity

Florida Bay salinity varies with time on a wide range of scales. Bay salinity normally reflects the annual wet and dry seasons driven by regional precipitation and temperature patterns, but also responds to episodic meteorological events such as tropical storms and cold fronts. In addition, Florida Bay salinities are influenced by interannual El Nino/La Nina cycles and by decadal variability in precipitation driven by Atlantic Ocean multi-decadal forcing. Variability on all of these time scales (and even longer scales the cause of which is completely unknown) can be seen in historical salinity and “salinity proxy”, i.e. paleoecological, data.

A preliminary analysis of historical data from the Salinity Synthesis database (Robblee et al., 2001) shows that for the past few decades the Bay has behaved as a marine lagoon with, on a few occasions, salinities as high as 70 reported in central Florida Bay. During drought years, salinity typically exceeds 40 over most of the Bay. Estuarine, i.e. mesohaline, conditions are rare in recent history and are associated with episodic events such as hurricanes and tropical storms or with other periods of above average rainfall, as occurred for example in 1994-1995. Increased water releases from the C-111 canal can also lower salinity across the Bay during relative dry years, e.g. 1983-1985.

Salinity variability is greatest in the northeast and decreases to the west. Boyer et al. (1997) and Boyer and Jones (2001) have described a decadal trend in monthly salinity values collected by Florida International University (FIU)'s Southeast Environmental Research Center (SERC) in Florida Bay from 1989-1999. Over this interval salinity in the eastern, central and western region declined 13.6, 11.6, and 5.6 respectively, but this "trend" is due largely to very high values during the 1989-1990 drought and is not descriptive of substantial interannual variability. For example, following the wet period of 1994-1995 salinity increased, tropical storms in 1999 induced a decrease, and data from the drought years of 2000 and 2001 indicated a further increase. More recent data from 2002 and early 2003 indicate another general freshening trend. (see SFERPM project website at www.aoml.noaa.gov/ocd/sferpm/surveymaps.html for monthly survey maps of salinity posted by NOAA's Atlantic Oceanographic and Meteorological Laboratory (AOML) and the University of Miami (UM)'s Rosenstiel School of Marine and Atmospheric Science (RSMAS).

Winds and Storms

In combination with upstream water management releases (due to flood control restrictions), storms can affect salinity by causing pulsed fresh water inflow events even in the “dry” season. Tropical storms can cause Everglades water levels to rise rapidly, and then recede slowly as fresh water seeps down into northeast Florida Bay. Northeasters drive fresh water out of the Everglades into Florida Bay. Biogeochemical materials in these fresh water flows follow similar input patterns (Cable et al., 2001). Higher salinity water moves from Florida Bay into the mangrove fringe area for several months during the dry season in typical years.

Along the southwestern coast of the Everglades, river discharge is affected by tidal forces but these can be masked by storm events (Levesque and Patino, 2001). Wind-driven flows can redirect low salinity plumes from discharges in the western Everglades into western Florida Bay and the Keys. Wind driven currents tend to advect water masses and realign salinity patterns in the direction of the flow, causing low salinity bands of river discharge and subsequent transport to connecting regions (Johns et al., 2001b). At present, the extent to which these plumes exchange with the interior waters of Florida Bay is unclear.

Over the last several years, a number of tropical cyclones have influenced the south Florida region through intense wind forcing, rainfall or both. D. Smith (2001), Johns et al. (2001b), and R. Smith et al. (2001) have recently shown that, although not as intense as in past periods of cyclone activity, these events caused significant and long-lasting (~months) changes in salinity patterns and turbidity in Florida Bay.

Precipitation and Evaporation

Florida Bay salinity patterns are a function of spatial and temporal patterns in precipitation, evaporation, runoff and exchange with the Gulf and Atlantic. Precipitation and evaporation are the two largest components of the Florida Bay water budget, yet we lack good spatial resolution for these components. Their respective positive and negative effects upon salinity are addressed under Driving Processes above. Interannual variations in salinity appeared to be affected primarily by fluctuations in rainfall, which not only falls directly into the Bay but also results in variations in the surface water discharged into Florida Bay from the southern Everglades.

An annual water budget for Florida Bay has been constructed using 31 years of salinity, hydrology and climate data (Nuttle et al., 2000; 2001). A simulation using a calibrated box model in which runoff was doubled decreased salinity in the eastern Bay, increased variability in the south, but had no effect in central or western regions of Florida Bay. From 1965-1995, annual runoff from the Everglades was one fifth of the annual direct rainfall into the Bay and annual evaporation slightly exceeded annual rainfall. On a seasonal basis rainfall, evaporation, and runoff were not in phase, leading to a strong seasonal pattern of salinity in the Bay.

Surface Water Inputs

Surface discharge from Trout Creek and Taylor Slough have significant influence on salinity patterns and variability in northeast Florida Bay where minimum salinity occurs near river mouths and strong gradients occur over the basin. In the fall, when sea level is relatively high, inter-basin exchange is enhanced resulting in more discharge reaching the central basin. The same can occur directly during tropical storms if the water table is sufficiently high (see Hurricane Georges Workshop report available at http://www.aoml.noaa.gov/flbay/hurgeocoverpage.html). Both help reduce hypersalinity in the Bay interior. River discharges, both remote and local to Florida Bay can be transported by coastal and boundary currents to different parts of the south Florida ecosystem for mixing and exchange. Under appropriate wind conditions, flow from rivers along the southwest Florida coastline can reduce salinities along the perimeter of the interior Bay and perhaps into its westernmost basins. Clear examples are the transport of the Shark River plume to western Florida Bay to help buffer salinity in that region (Lee et al., 2001a; 2001b) and the transport of Mississippi River waters to the Florida Keys (Ortner et al., 1995). Exchange of surface water discharged into the western Bay with adjacent interior basins is not well understood at present, and new observations are underway to better resolve these processes.

Groundwater Inputs

No large-scale effects of groundwater on salinity have been observed. Observing this input is made more difficult by the fact that the primary groundwater input is thought to be saline. However, anecdotal evidence reports the existence of local springs and these have been observed by scientists in nearby Biscayne Bay at least in the very near shore within a few hundred meters of the shoreline (J. Proni, pers. comm.).

Sea Level and Tides

At times of high sea level in the fall especially during and after tropical storms, overland flow can occur directly into the central basin thereby reducing hypersalinity (see above). On the other hand, low sea level can restrict exchange between adjacent basins by minimizing overbank

exchange. Runoff to central Florida Bay probably is more common in the fall tropical storm season when annual water levels are relatively high, but could occur at any time of the year. Higher water levels may facilitate movement of this fresh water across banks to the south and west. However, seasonal or wind induced high water along the northern boundary may also hinder fresh water flow to the Bay by reducing the head gradient.

Boundary Currents

Ortner et al. (1995) and Lee et al. (2001a, 2001b) have clearly shown that remote sources of fresh water in the eastern Gulf of Mexico, transported by boundary currents, can have significant impact on the salinity patterns in south Florida coastal waters including the westernmost regions of Florida Bay. Boundary currents surrounding south Florida coastal waters can also change sea level slopes and Gulf-Atlantic flows through western Florida Bay that enhance Bay exchange with adjacent waters.

Circulation

The interior portion of Florida Bay is made up of a complex maze of shallow basins separated by mud banks and mangrove islands. The Bay is openly connected to the southwest Florida shelf along its wide western boundary, but exchange with the Atlantic coastal zone of the Keys is restricted to a few narrow tidal channels through the Keys island chain. The northern boundary is mangrove fringed, with fresh water input in the northeastern region through Taylor Slough and Trout River. The rapid fall-off of tidal range with distance from the western boundary, and the dramatic increases in salinities observed in the interior basins, indicate poor water exchange between the northeast and central portions of the Bay with adjacent subregions.

The entire south Florida coastal ecosystem, except for the interior of Florida Bay, is highly connected by a regional recirculation system. This regional circulation is driven by the combined forcing of winds, sea level slopes, oceanic currents such as the Florida Current and Loop Current, and eddies at the offshore boundaries (Lee and Williams, 1999; Lee et al., 1999; Lee et al., 2001a). Seasonal patterns in wind forcing result in seasonal shifts in the regional circulation system and preferred pathways of exchange between waters of the southwestern Florida shelf (including the near shore waters of the southwest Everglades and western Florida Bay) and the waters of the Keys Atlantic coastal zone. Everglades discharges are typically advected southeastward through western along the western boundary of Florida Bay's interior and the channels of the middle Keys to the reef tract in the winter and spring, toward the Tortugas in the fall, and northwestward to the west Florida shelf in the summer, followed by entrainment by the Loop Current and return to the Keys coastal zone (Lee et al., 2001a). Advective time scales to reach the Keys Atlantic coastal waters range from 1-2 months in winter, spring and fall and up to 6 months in the summer.

Winds and Storms

The coherent mesoscale and synoptic scale wind forcing causes alongshore barotropic currents that are geostrophically balanced by coastal sea level on either side of the Keys, as well as cross-Key sea level slopes that drive exchange with Florida Bay on several day to weekly time scales. A strong alongshore current response to alongshore wind forcing was found for the Keys Atlantic coastal zone (Lee and Williams, 1999) and for the southwest Florida shelf (Lee et al. 2001a) for synoptic scale and seasonal scale winds. The seasonal pattern of the wind forcing results in seasonal circulation patterns that link the south Florida coastal waters along the western

boundary of interior Florida Bay (Lee et al., 2001a): southward Gulf to Atlantic flows in winter and spring; northwestward to the Gulf in summer; and southwestward toward the Tortugas in fall. This pattern is clearly demonstrated in the trajectory pathways of Lagrangian drifters that have been regular released over the past few years (Fig. 4.4).

Cross-shelf mean flows on the southwest shelf and the western boundary of interior Florida Bay indicate an estuarine-like circulation with offshore flow in the upper layer and onshore in the lower layer, suggesting a response to prevailing eastward winds and buoyancy forcing from fresh water discharges through the western Everglades.

The transient effect of storms upon circulation depends upon wind strength, direction and duration. Large increases in current speeds have been observed in western Florida Bay and along the southwest Florida shelf and Keys coastal zone with the passage of tropical storms (Johns et al., 2001b).

Precipitation

Precipitation has not been observed to have any direct effects upon circulation.

Evaporation

Evaporation has also not been observed to have any direct effects upon circulation. However, some anti-estuarine flow (flow toward areas with high rates of evaporation) presumably results from net evaporation during the dry season.

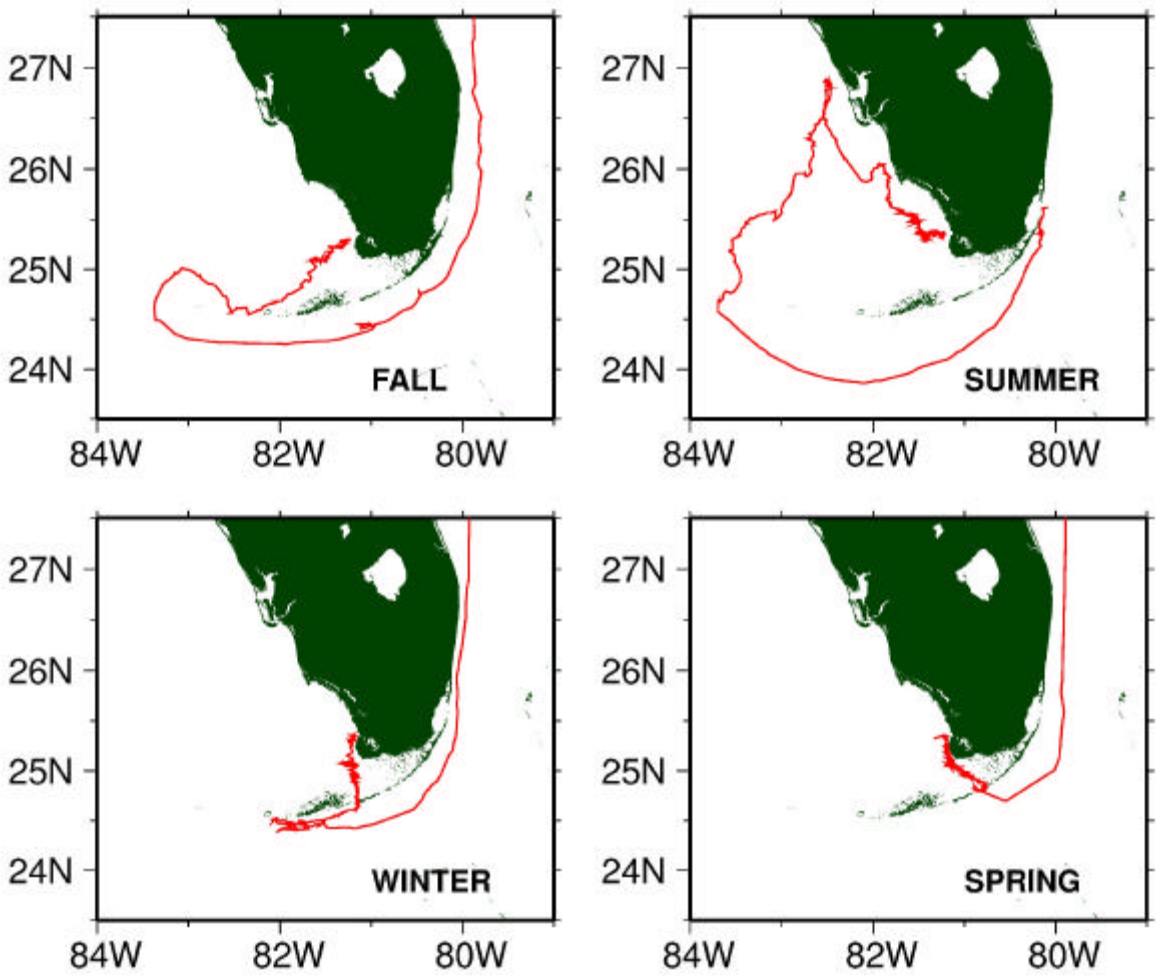
Surface Water Inputs

Surface water inputs through the small rivers of the western Everglades tend to form a low salinity band in the near shore waters that is entrained by coastal currents and transported to western Florida Bay and the Keys (Johns et al., 2001a). This is a passive response to existing circulation. The amount of buoyancy forcing from these small rivers (5-30 m^3/s) appears to be insufficient to produce a dynamic coastal current within the low salinity plume. Salinity observations do indicate that fresh water discharges to the northeast Bay tend to move slowly to the south and west and can serve as a passive tracer of the Bay's interior circulation.

Groundwater Inputs

Isotope-derived estimates of groundwater inputs to Florida Bay vary by several orders of magnitude (see above under Driving Processes). Efforts are underway by USGS and SFWMD to resolve this discrepancy by applying improved hydrological models. Groundwater forcing is not included in present Bay hydrodynamic or water budget models and does not appear necessary for conservation of mass or for simulation of large seasonal salinity cycles. The between-basin flows that would result from the higher estimates are also inconsistent with available intra-basin flow observations.

Figure 4.4: Representative seasonal trajectories of satellite-tracked surface drifters (Lee et al., 2002).



Sea Level and Tides

Water movements occur on time scales ranging from minutes to seasons to years. Tidal currents often account for a large part of the variation in coastal currents and are important for local mixing and dispersion of materials. However, because of the regular reversal of tidal currents, they are not efficient transport mechanisms over distances larger than a few kilometers. In the interior of the Bay, cross-bank sea level slopes are believed to have an important influence on driving flows between basins and ultimately on residence times. Subtidal or low frequency currents driven by sea level slopes caused by wind or offshore boundary currents are primarily responsible for linking adjacent as well as remote regions to south Florida ecosystems. Cross-Key sea level slopes drive flows through the Keys tidal passages at tidal and subtidal frequencies that couple the Gulf and Atlantic coastal regions of south Florida (Lee and Smith, 2002).

Boundary Currents

While boundary currents are the dominant feature of the regional circulation, within Florida Bay their effect is indirect. Long-term moored current observations indicate a mean southward flow on the southwest Florida shelf that can transport eastern Gulf waters, including river discharges from the west Florida shelf and Mississippi River, to the Tortugas and through western Florida Bay to the Keys coastal zone (Lee et al., 2001a). The origin of the mean flow is not clear, but the position of the Loop Current appears to influence mean flow magnitude and may be the driving force. To more fully understand the relevant processes will depend upon rigorous calibrated regional model simulations incorporating field observations and satellite data.

Exchanges with Adjacent Waters

Exchanges with adjacent waters are related to three of the driving forces that have been discussed above, specifically winds and storms, sea level, and boundary currents. Waters of the interior portion of Florida Bay interact with waters from two very different continental shelves: the wide, north-south oriented southwest Florida shelf to the west and the narrow, curving Keys coastal zone to the east and south with its shallow reef tract topography. These two shelf regions exchange waters with each other through the tidal channels between the Keys and they also exchange waters with the strong oceanic currents at their outer edges: the Loop Current in the Gulf of Mexico and the Florida Current on the Atlantic side of the Keys. There is strong interaction with the Florida Current through eddy processes throughout the Keys shelf domain. That a similar process occurs along the outer edge of the southwest Florida shelf is apparent in satellite imagery, water property distributions and model results. Recent drifter trajectories (Yang, 1999) indicate that there is a discontinuity between midshelf waters in the region offshore of Tampa Bay which is possibly related to the amplitude of river discharge.

Preliminary results from current measurements by N. Smith (2002) in several channels connecting interior sub basins of Florida Bay suggest a general southward motion of waters from the north central region of the Bay that seems to diverge toward the Atlantic and Gulf in the southeastern region of the Bay. Exchange between basins appears to be strongly influenced by wind direction as well as magnitude. Little is known about the physical processes that regulate water renewal in the Bay's interior or the preferred pathways of circulation.

Mean flows through the western boundary of interior Florida Bay (between East Cape and Marathon) are roughly estimated from long-term current observations and indicate inflow

(eastward) of about 1300 m^3/s in the northern portion and outflow (westward) of about 300 m^3/s in the southern region, giving a net inflow across the section of about 1000 m^3/s (Smith and Pitts, 2001; N. Smith, 2002). Since 400-500 m^3/s of this inflow exits southward through the middle Keys passages, then approximately 500 to 600 m^3/s is available for transport into interior regions of Florida Bay. Tidal, subtidal, and long-term transports into Florida Bay are neither well resolved nor understood. Also it is not clear what portion of the net inflows to the Florida Bay interior are used to balance mean sea level rise, account for evaporation water losses, or drive residual circulation. Observations have also quantified tidal period transports (N. Smith, 2002). To some degree, mixing during tidal exchanges must import Gulf and Atlantic water to Florida Bay and export Bay water to the Gulf and Hawk Channel. The net exchange due to this process has not yet been quantified and will require calibrated model simulations in addition to observations to resolve.

Winds and Storms

Wind forcing was found to set up cross-Key sea level slopes that can drive large flows into or out of western Florida Bay (Lee and Smith, 2002). Strong east and northeast winds during the fall cause a positive cross-Key slope and inflow to the Bay from the Atlantic. Gulf to Atlantic outflows from the Bay are associated with negative cross-Key sea level slopes from southeast, west, and north winds typical of summer, winter, and spring. Wind-driven exchanges through the middle Keys can produce net flows of 1000 to 2000 m^3/s over the duration of the event, typically 1 to 10 days for Long Key Channel alone and possibly 2-4 times this amount for all of the middle Keys channels.

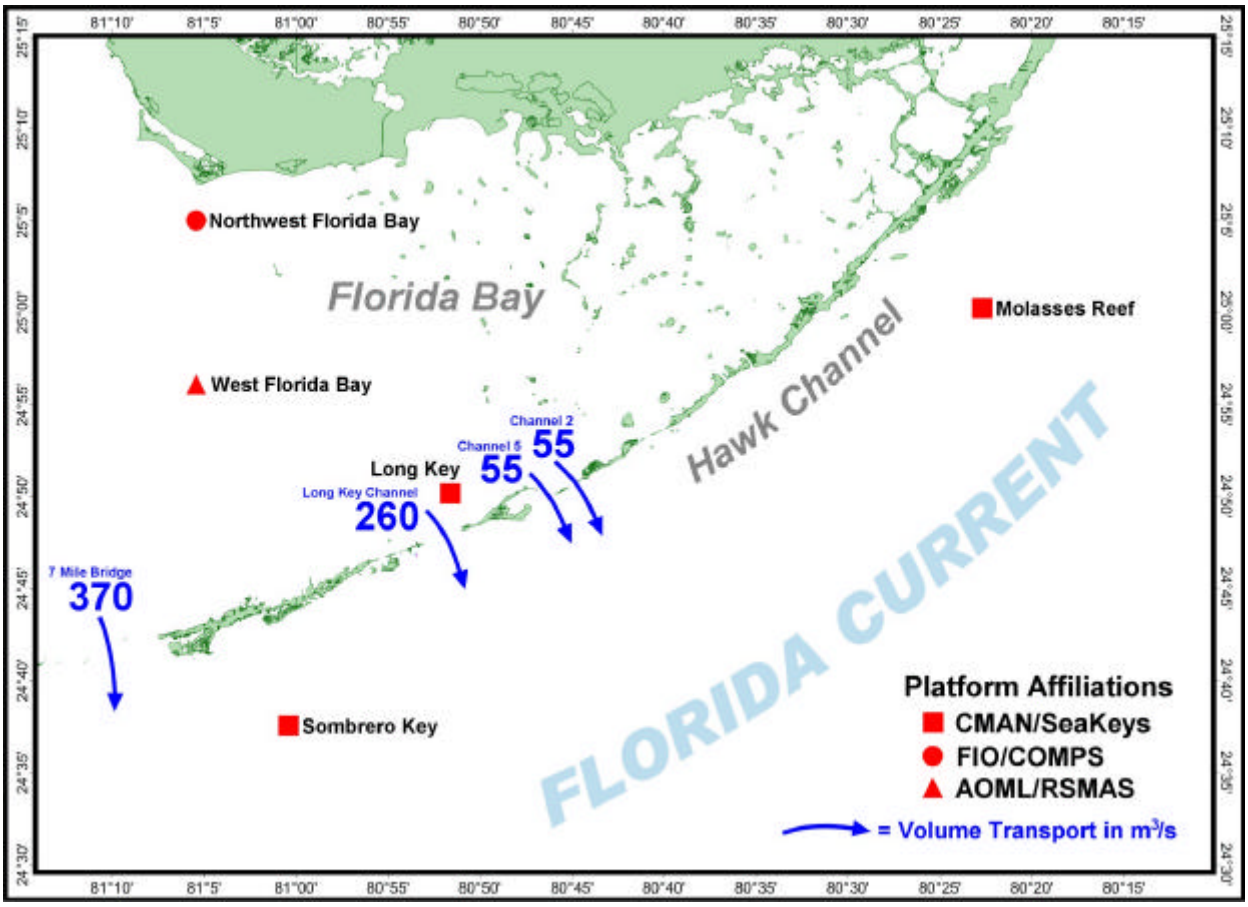
Recent current measurements in the main shipping channel at Key West indicate a net northward flow to the Gulf that appears to be related to the prevailing westward winds and suggests an Ekman response in the Keys coastal zone (Smith and Pitts, 2001). The magnitude of this flow has not yet been determined. However, when combined with the Gulf to Atlantic flows in the middle Keys, this information provides an indication of a possible clockwise recirculation around the lower Keys.

Sub-tidal transports through passages in the upper Keys are much weaker than the middle Keys and appear highly influenced by onshore/offshore winds that may cause a set-down or set-up of water level in northeastern Florida Bay (N. Smith, 2001).

Sea Level and Tides

It is clear that the volume transports through the Keys passages are produced by cross-Key sea level slopes and that low-frequency changes are strongly dependent on wind forcing over the dynamically different shelf regimes on either side of the Keys. The strongest flows occur in the middle Keys channels where the combined subtidal outflows toward the reef tract can be as high as 7000 m^3/s during winter cold front passages and inflows to western Florida Bay can reach 2800 m^3/s during fall northeast wind events. The magnitude of these flows is 100 to 200 times larger than the total fresh water inflows to Florida Bay. The mean flow through the middle Keys passages is estimated at approximately -800 +/- 100 m^3/s toward the reef tract (Fig. 4.5). The cause of the mean flow is uncertain but it appears to be related to the mean sea level difference between the Gulf and Atlantic and may be influenced by the Loop Current position. A series of investigations by N. Smith (1998), Smith and Lee (2001), Lee and Smith (2001), Smith and Pitts

Figure 4.5: Average subtidal flow through the middle Keys passages (Lee and Smith, 2002).



(2001) and N. Smith (2001) have quantified the magnitudes and variability of the inflows and outflows of Florida Bay through the Keys tidal passes and across the western boundary in the Gulf transition region.

Boundary Currents

Boundary currents provide the coupling of the Gulf and Atlantic through western Florida Bay via sea level differences and along the seaward edges of the Gulf and Atlantic shelves through eddy and wind-driven exchanges (Lee et al., 2001a, 2001b). Boundary currents can transport remote waters including river discharges near to the Bay and eddies shed by these currents and related dynamic mesoscale features can enhance exchange with adjacent shelf regions. Continued monitoring and modeling of boundary currents and their relationship to local circulation and exchange processes is essential.

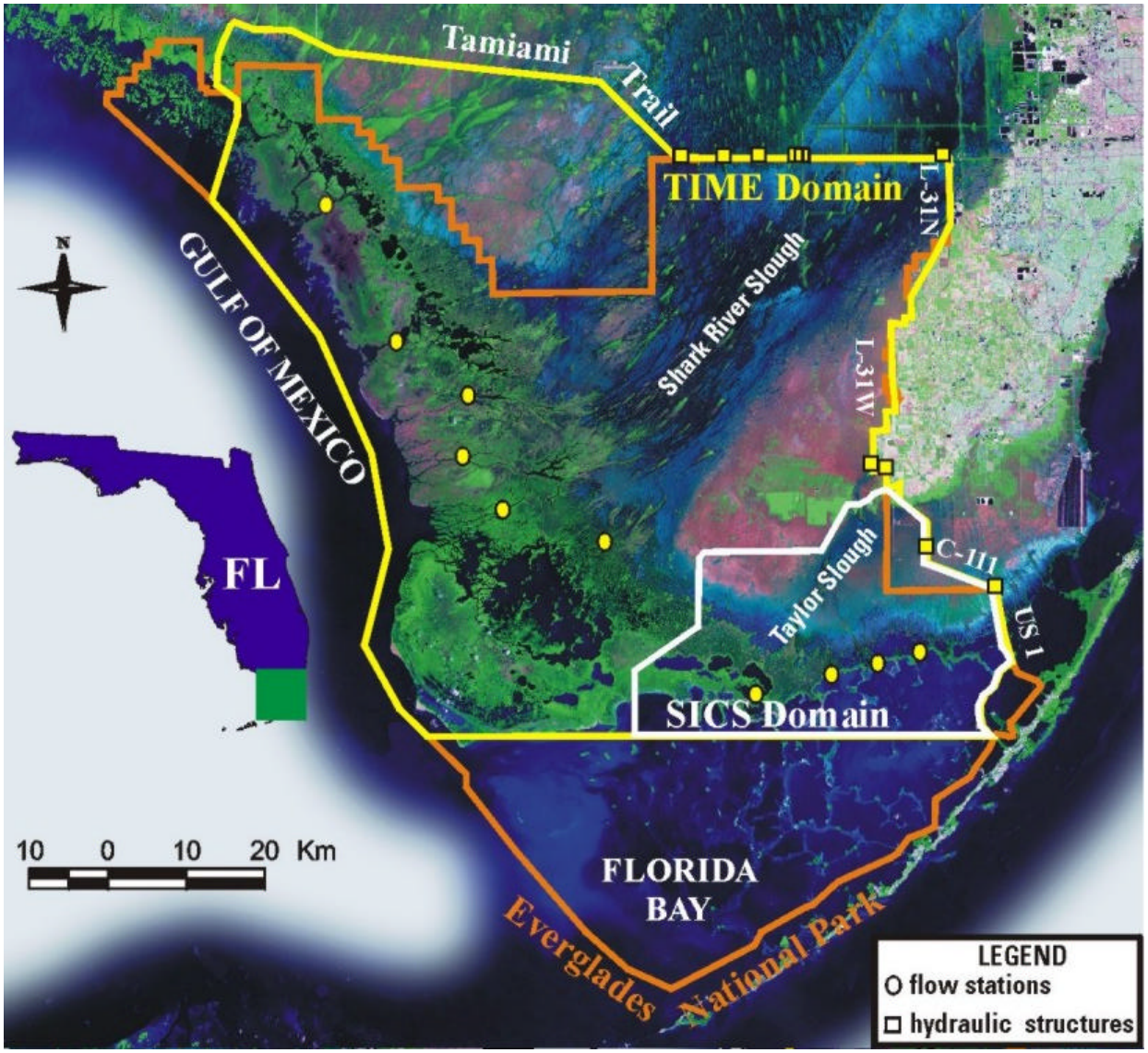
Prediction

Observational data alone are not sufficient to predict salinity patterns, circulation, fresh water input and exchanges with adjacent waters under different restoration and climatic scenarios. Due to the physical complexities of the Bay, these data need to be complemented by calibrated models, a number of which are listed below.

Fresh Water Inflow

To predict salinity, hydrological models that can provide estimated runoff at the hydrodynamic model's terrestrial boundary are essential. The fresh water discharge model must also be able to estimate runoff under various Comprehensive Everglades Restoration Plan (CERP) alternatives. The USGS has developed a hydrodynamic transport model to simulate flow and salt fluxes through connected surface and ground-water systems. A numerical algorithm has been developed to synchronize surface-water tidal-compatible time steps with groundwater stress periods and to assure mass conservation of simulated flux quantities across the surface/groundwater interface and land-surface boundary in the coupled model (Swain and Langevin, 2001; Swain et al., 2002). Hydraulic expressions derived from hydrologic process studies in the Everglades have been formulated to link flow resistance, wind stress, and evapotranspiration processes to the vegetation properties and shallow flows typical of these low-gradient wetlands. Two applications of the coupled model have been made that are largely within the confines of ENP (Fig. 4.6). The Southern Inland and Coastal Systems (SICS) model encompasses the Taylor Slough wetlands, part of the C-111 drainage basin, and sub-tidal embayments along the northern coastline of Florida Bay. The Tides and Inflows in the Mangrove Ecotone (TIME) model encompasses the SICS model domain, Shark River Slough, other western sloughs, and subtidal embayments and tidal creeks along the southwest Gulf coast. Measured surface water flow discharges, water levels, and salt concentrations at tidal creeks, wetland water levels and flow velocities, and groundwater heads and salinities supplemented by subsurface salinity maps and soil properties are used for model calibration and verification. Tide levels and salt concentrations along the coast and discharges and water levels at hydraulic control structures, bridges and culverts are used to drive the SICS and TIME simulations. The models simulate flow exchanges and saltwater fluxes between the surface and groundwater systems in response to these multiple driving forces, which could be altered based on proposed changes to

Figure 4.6: South Florida satellite image showing SICS and TIME model domains (USGS).



the system. Insight into flow patterns and salt fluxes, which only can be obtained through hydrodynamic transport models, is needed to fully evaluate the potential impact of restoration decisions for the greater Everglades on ecologically sensitive land-margin ecosystems bordering the northern coastline of Florida Bay and the southwest Gulf coast of Everglades National Park.

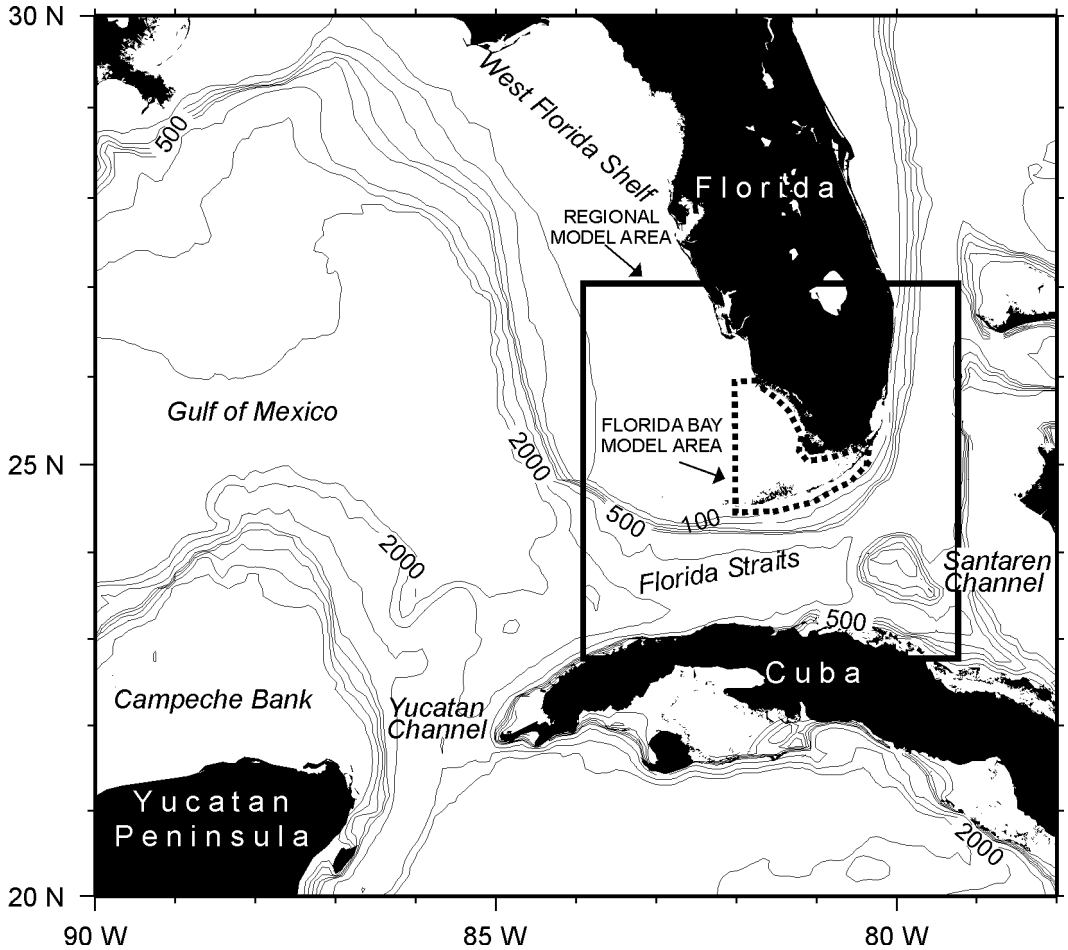
Exchanges with Adjacent Waters

The predictions needed from Florida Bay numerical circulation models can only be carried out with suitable inputs along their boundaries. This is necessary to introduce the complex interactions that dominate circulation and water exchange between the shallow Bay interior and the adjacent shelf and oceanic flows. The boundary conditions must cover a range of time scales to accommodate different types of simulations planned by the inner Florida Bay modeling teams (interannual, seasonal and event oriented simulations). Existing global models are not suitable for this task, due to their coarse resolution and the lack of flexibility in performing simulations that match currently planned and future Florida Bay modeling activities. Therefore, it is necessary to develop a regional-scale numerical model that will perform simulations that are closely linked to interior Florida Bay modeling needs. The regional model must be dedicated to the computation of the required hydrodynamic fields surrounding the Florida Bay model domain and to the calibration of these fields with observational data. Such a model is under development that applies the three-dimensional, finite difference community hydrodynamic model HYCOM (Hybrid Coordinate Ocean Model, http://panoramix.rsmas. miami.edu/hycom/) on the seas adjacent to Florida Bay and the Florida Keys, including the Florida Straits, the western Gulf of Mexico and the southwest Florida Shelf (Fig. 4.7). This model is being coupled with an existing, large scale, coarse resolution application of HYCOM that includes the North Atlantic, the Gulf of Mexico and the Caribbean. This nested approach ensures the interaction of Florida Bay models with the Loop Current, Florida Current and related eddies, as well as remote sources of river induced low salinity.

Circulation Models

To understand circulation and exchange within the interior of Florida Bay, a fully calibrated and verified numerical circulation model is needed. The growing database of salinity, currents, volume transports, surface and groundwater inputs and atmospheric forcing is rapidly becoming sufficient to provide comprehensive evaluation and validation of circulation models. To this end, a Standard Data Set has been agreed upon and is under development (J. Pica, pers. comm.). Indeed, the complexities of Florida Bay demand a suitable modeling approach to properly evaluate possible future water delivery schemes to the Bay. There are expertise and modeling resources available that can be applied to this problem in a reasonable time frame. However, two particular problems need to be addressed urgently: a) the bathymetry, which is not currently available at the detail needed by the models; and b) appropriate inputs at the boundaries of Florida Bay models, needed to introduce the complex interactions between the shallow coastal areas within Florida Bay and the adjacent oceanic flows. Both the bathymetry and the boundary conditions must be part of an integrated modeling approach that includes parallel, coupled numerical simulations in Florida Bay and the adjacent seas. This comprehensive modeling tool must get underway soon to match with the observational programs and to advise management in a timely manner.

Figure 4.7: A nested model approach. Planned regional South Florida model area (thick solid line). Thick dashed line marks the Florida Bay and Florida Keys model area. The oceanic waters surrounding the regional model domain are included within the University of Miami's large-scale North Atlantic, Caribbean and Gulf of Mexico model (HYCOM).



Salinity Models

To understand and predict salinity variability in Florida Bay three types of models have been applied: statistical (regression analyses), mass-balance and mechanistic. (The third type will be discussed below under Unresolved Questions and Ongoing Research.)

Statistical Models

The PST sub-group evaluating salinity performance measures recommended a two-phase plan to develop updated salinity performance measures to predict fresh water runoff. First, a multi-variable linear regression model using lagged terms should be constructed. Second, a time series model relating the fresh water flows from the operation of the C-111 Canal to the salinity of the near shore embayments should be prepared for use in management decisions. A follow-up meeting recommended that the use of Seasonal, Autoregressive, Integrated Moving Average (SARIMA) models be explored. A preliminary evaluation of current salinity performance measure relating water levels in the Everglades to the salinity in northeast Florida Bay has been reported on (Marshall, 2001). Problems with the use of linear regression models for this data set were identified, particularly seasonality, cross correlation, and autocorrelation of hydrologic parameters. At that time models and modeling techniques were not capable of adequately simulating the effect of changes in operations of the C-111 Canal.

Mass Balance Models

Box models by Walker (1998), Nuttle et al. (2000; 2001), Cosby et al. (1999), and Twilley (http://www.ucs.louisiana.edu/~rrt4630/mangrove-restudy.htm) apply mass balance calculations to the analysis of wetland hydrology, Florida Bay salinity, and the salinity of Shark River, respectively. In all cases, these models incorporate simplified representations of water flow that are parameterized by matching model prediction to observed hydrology and salinity.

Walker (1998) implemented a set of watershed hydrology models in Everglades National Park. These were used to estimate water and nutrient fluxes into the coastal mangroves. The models constructed monthly water budgets for several wetland basins based on data provide by the 2x2 hydrology model. The aggregated discharge from each basin was assumed to be related to mean water depth by a generalized power law. The parameters of this power law were estimated by fitting simulated water depths to observations. Over the long term, the mean outflow from the basins must be correct, if the data on other terms in the water balance are accurate. The parameters of the flow model control the variation of estimated flows around the long-term mean value. Walker (1998) lacked the outflow data necessary to validate his watershed models, but did find that predicted outflows were correlated with salinity in the coastal bays in the Taylor Slough/C111 area.

Nuttle et al. (2001) implemented a mass balance model in Florida Bay for estimating evaporation. This model calculates salinity, using monthly time steps, from variation in the net supply of fresh water to and water exchange between each of four regions in the Bay, and exchange with the Gulf of Mexico. The regions used in this model correspond to the regions defined from similarities in water quality (Boyer et al., 1997) and other attributes of the Florida Bay ecosystem. Rainfall and salinity used to drive the model are measured in the Bay. Fresh

water runoff is estimated from measured flows in Taylor Slough and the C111 canal that discharge into the mangrove wetlands north of the Florida Bay. The four-box model by Nuttle et al. (2001) has been calibrated against salinity data for the period 1993 through 1995 and validated by comparison with salinity data in the period 1996 through 1998. The standard error of prediction is about 2 ppt across all four regions. Calibration of the model produces estimates for the unknown seasonal evaporation rates and the exchange rates between basins and with the Gulf of Mexico. These exchange rates can be used to investigate residence times in the Bay, information that is needed to understand the processes that control nutrient concentrations and plankton blooms.

Nuttle et al. (2000) employ two different box models. One is essentially the annual averaged version of the four-box model described above, which they use to estimate mean annual evaporation from Florida Bay. The other, FATHOM (Cosby et al., 1999), divides the Bay into about 40 basins, based on its morphology, and estimates exchanges between basins based on tide-driven hydraulic calculations. FATHOM has been applied to analyze the influence of changing runoff into Florida Bay (Nuttle et al., 2000), but the calculated exchange rates and resulting residence times have yet to be validated by comparison with observation.

Twilley (http://www.ucs.louisiana.edu/~rrt4630/mangrove-restudy.htm) models salinity in the Shark River using boxes representing upper and lower reaches along the channel. The model includes the effects of advection, estimated from long-term records of fresh water flow, and dispersion determined by calibration. This is one of a set of models under development as part of a study of mangrove forest dynamics.

Unresolved Questions and Ongoing Research

Driving Processes

Winds and Storms

Although the synoptic scale and seasonal winds over south Florida coastal waters appear to be highly coherent over the whole region, there is now evidence from high resolution numerical atmospheric models (Mattocks, 2001; Chen et al., 2001) that indicates considerable spatial variability as a result of mesoscale activity associated with convective systems and sea breeze development. A number of questions remain: What are the long-term effects of the daily development of convergent wind patterns over the Bay? What are the magnitudes and spatial and temporal scales of this mesoscale wind forcing? How does it influence the south Florida seascape in terms of water levels, evaporation and precipitation patterns, circulation and exchange between water bodies, and surface and groundwater inflows to the Bay? What is the effect of winds on residence times of the interior waters of the Bay? It is not clear what changes may occur from intense cyclones, nor how long these changes may persist. Predictive modeling of different classes of tropical cyclones is needed to anticipate these impacts.

Precipitation

Considerable progress has been made with regard to the process of making precipitation observations into an operational product. Applicable NEXRAD data fields have been mapped

onto the SFWMD hydrological (2x2) grid and are now being archived at the SFWMD. Use is now being made of locally generated statistical functions relating radar reflectance to tropical convective rainfall (Willis, 2001). As a result we are now ready to address a number of unresolved questions in regard to precipitation such as: Do the spatial patterns of Bay surface salinities measurably change as a result of the heterogeneity of precipitation? To what degree has precipitation over the Bay been changing because of land use changes on the peninsula?

Evaporation

Price et al. (2001) describe an investigation that is designed to provide mean rates of evaporation and its variation both spatially and temporally in Florida Bay. This investigation will be the first systematic attempt at determining evaporation in Florida Bay and tying mean estimates of evaporation with longer term monitoring efforts ongoing in the Bay. Questions to be answered by this project include: What is the mean rate of evaporation in Florida Bay? What is the spatial and temporal variation of evaporation? How reliable are long-term estimates of evaporation? How much additional precision can be gained by refinement of stable isotope methods?

Other questions regarding evaporation include: To what degree does the seasonality of evaporation need to be considered in evaluating the effect upon salinity patterns of different water management scenarios? What is the effect of the Bay's bank and basin topography upon evaporation? The rate of evaporation over the extensive, shallow banks may be different from the average estimates used to date. Neither instrumented platform meteorological data, nor synoptic radiation surveys, have characterized conditions over shallow, seasonally exposed banks. Although the radiation forcing over the banks will be the same as elsewhere, the different characteristics of the water column (shallow) and bottom (dense sea grass) are expected to affect how outgoing heat flux is partitioned, which could in turn significantly change local evaporation rates.

Surface water inputs

Simulation models under construction by the United States Geological Survey (USGS) and the SFWMD in conjunction with their ongoing measurement programs are expected to resolve any remaining uncertainty concerning surface water discharges into Florida Bay. Hydrodynamic transport models have been developed that are capable of being linked to upland management models to address the impact of fresh water inflows on tempering salinities and conveying nutrients and contaminants to Florida Bay and southwest coastal estuaries. Langevin et al. (2002a) of the USGS have developed a coupled surface/groundwater model of the southern Everglades that is capable of simulating flow and salinity patterns in coastal embayments of northern Florida Bay in response to naturally occurring hydrologic events in the wetlands and the effects of upland management practices on fresh water releases. The model provides the capacity to evaluate the complex exchange and interaction of water and dissolved salt among the Everglades wetlands, the Florida Bay estuaries, and the underlying Biscayne aquifer. Further enhancements of the model are ongoing and its computational domain is being extended to include Shark River, Lostmans River, and other western sloughs south of Tamiami Trail within Everglades National Park (Schaffranek et al., 2002). Both models are being developed at temporal and spatial resolution scales that are facilitating the formulation of new estuarine species models (Cline and Swain, 2002) in the Across Trophic Level Simulation System

(ATLSS) to assess the ecological health of the total ecosystem and to develop and evaluate performance measures within CERP (DeAngelis et al., 2002).

Groundwater inputs

The discrepancy between isotope-derived estimates and the more traditional hydrological approaches (well heads and models) has been discussed above as has the discrepancy between mass balance and flow observations and isotope estimates. Clearly many unresolved questions remain concerning not only the absolute amount of groundwater input to Florida Bay but also its temporal and spatial variability and the resulting salt and nutrient flux. The consensus at present is that the water quality implications of groundwater input from either the southern Everglades or Florida Keys may be more significant than its physical consequence unless the larger estimates prove to be correct.

Sea level and Tides

No major unresolved issues remain concerning tides. Studies are underway concerning the effects of sea level differences on inter-basin exchange and upon flow through the passages between the Florida Keys. It is also not clear how long-term sea level differences between the Gulf and Atlantic affect the observed mean southeastward flow that transports water to the Florida Keys reef tract.

However, Frederick et al. (1994) and others have noted acceleration in local sea level rise over the past century. The extent of this is not entirely clear nor is there yet an adequate geophysical explanation. Such a sea level rise would certainly have implications concerning Bay restoration targets. A SFWMD study has concluded, however, that the currently projected sea level rise does not substantially affect CERP project water deliveries. While not precisely a “research issue”, additional tide gauge benchmarks are needed near each water level recorder in Florida Bay and all the Gulf coast stations to obtain absolute sea level measurements. A number are in place but many others remain to be driven. The USGS mapping division and USGS St. Petersburg laboratory are currently working to establish elevations at many Gulf coast platforms.

Boundary currents

Questions concerning the effect of Boundary Currents are given below under System Characteristics. Modeling and observational studies are continuing to address how boundary currents are influencing the variability of flow through Florida Bay and the exchanges that take place between boundary currents and adjacent shelf waters.

System Characteristics

Salinity

Although the spatial and temporal variability of salinity in Florida Bay is well documented and continues to be monitored both with field surveys and fixed instruments, a number of unresolved questions remain, such as: How is the salinity of Florida Bay influenced by atmospheric forcing on time scales from daily to inter-decadal, including significant transient meteorological events such as hurricanes and tropical storms? How do the spatial patterns of evaporation, precipitation and basin residence time affect Bay salinity distributions? For example, does hypersalinity occur where it does because evaporation is greater over broad shallow banks than in the rest of the Bay, or because exchange with lower salinity water is restricted? How do the salinity records inferred

from paleoecological data compare with salinity values measured over the past 45 years? Is there a statistical transfer function sufficient to adequately describe the effect of fresh water flows on salinity for the purposes of predicting the effect of restoration scenarios upon Bay salinity? If so, over what spatial domain does it apply?

Circulation

Circulation and exchange between isolated basins in the interior of the Bay is the subject of several ongoing field research projects and will be a focus of the forthcoming interior Florida Bay model. Scientists from RSMAS, AOML), Harbor Branch Oceanographic Institute (HBOI), ENP and the USGS have at various times been maintaining arrays of current, temperature, salinity, and water level recorders within basins and channels during wet and dry seasons. Also included are shipboard Acoustic Doppler Current Profiler (ADCP) observations and direct measurements of transports, salinity surveys, and surface drifters. These data will be used to directly compute salt transports, water exchange, and interior circulation. In contrast, the exchange between the Gulf of Mexico and western areas of the Bay has yet to be quantified. Doing so is one of the principal unresolved questions concerning circulation.

A better understanding of flow across banks, and bank characteristics in general (e.g. cover, elevation, salinity, and temperature), will be necessary for successful hydrodynamic and ecological modeling of the Bay interior. The bathymetry of Florida Bay, particularly with respect to the shallow banks, needs to be more adequately described for use by modelers. It is not clear to what degree remote sensing (LIDAR) can be used to address this deficiency, given the density of seagrass. The depth over many of the banks is approximately equal to or less than the range of seasonal fluctuations in mean sea level. What consequences might this have for rates and patterns of inter-basin water exchange in the interior portion of the Bay? What are the rates and pathways of exchange between the interior basins and across the banks in the western, central, and eastern regions of Florida Bay and with the southwest Florida shelf?

On a regional scale very little is known about the cause of the net southward flow that couples the eastern Gulf and Atlantic coastal region of the Keys, and its long-period variations. This flow transports low salinity discharges from rivers in the eastern Gulf and western Everglades around Cape Sable to western Florida Bay where they can interact with interior waters of the Bay as well as the Atlantic coastal waters of the Keys. It is essential to better describe and understand this flow in order to aid future model development and facilitate informed management decisions. What is the influence of the Loop Current or synoptic winds over the west Florida shelf on driving this flow? Are topographic constraints on the southwest Florida shelf important? How is the flow related to observed southward flows farther north on the west Florida shelf that appear to diverge away from the coast before reaching the southwest shelf (Yang et al., 1999)?

Exchanges with Adjacent Waters

During the dry season, high salinity waters from western Florida Bay and the Gulf transition region are transported southward toward the Florida Keys National Marine Sanctuary (FKNMS). There is evidence from the large-scale hydrographic surveys that at times these high salinity waters can form a near-bottom salty layer in the Hawk Channel region. However, very little is known about this process. How

are the salty bottom layers formed? What are their spatial extent and transport pathways? What are their durations?

Analysis of current records taken in different years suggest that a transport of up to 500 to 600 m^3/s could be available for exchange with the interior of Florida Bay. Transports across the western boundary are very uncertain at this time; however, field research is planned to improve understanding of transport processes and help quantify this exchange. There are also unresolved questions regarding the bank "overtopping" process, and whether this could explain the observed net outflow from the central part of the Bay.

Mean Gulf to Atlantic flows through western Florida Bay to the Keys coastal zone and reef tract have been estimated from observations and are believed to be connected to the boundary currents (Loop Current and Florida Current) surrounding south Florida (Lee and Smith, 2002). More effort is needed to quantify and monitor this mean flow to better understand the physical processes involved. Is it related to the position and configuration of the Loop Current as Gulf models and satellite observations suggest? Coupling of a large-scale model that includes the Gulf and Straits of Florida to a finer scale Florida Bay model is needed to address this issue.

Hydrodynamic Models

Research aimed at developing and applying mechanistic models has pursued two radically different approaches. These are the aggregated representation of hydrology and salinity in mass-balance models, described above, and the detailed representation of tide and wind-driven water movements in wetland hydraulic and estuarine hydrodynamic models, for example the RMA-10 model (Kim et al. 1999). The PST reviewed the RMA-10 some time ago and little work has proceeded on it since that time. The review raised fundamental concerns both in regard to the degree to which the model was calibrated and verified and in regard to more basic issues such as boundary conditions and transport processes within the Bay interior (http://www.aoml.noaa.gov/flbay/pmcphysci.html). J. Wang (pers. comm.) has recently applied the finite element model CAFE3D in 2-D mode to determine salinity fields in Florida Bay resulting from a "climatological" run-off hydrograph and with realistic winds and tides. Multiyear simulations have been made and show patterns similar to observations (http://anole. rsmas.miami.edu/people/jwang/Florida_Bay_Model.html).

The Florida Bay and Florida Keys Feasibility Study (FBFKFS) of CERP convened a Hydrodynamic Model Review Workshop in June 2002, with a Review Panel to assess prospects for the successful modeling of Florida Bay hydrodynamics as a management tool. This Panel provided strong support for the development of a numerical hydrodynamic model based on the need to support water quality and seagrass modeling of the Bay. The Panel also firmly recommended not to combine different numerical modeling frameworks (specifically, hybrid mixing of finite element and finite difference numerical grid solutions for hydrodynamic and water quality modeling). The Panel’s recommendations were generally consistent with the Physical Sciences Team’s previously issued Modeling Terms of Reference.

During this workshop, the SFWMD described their exploratory analysis to determine the feasibility and applicability of a finite difference model, based on the Environmental Fluid Dynamic Code (EFDC), for Florida Bay. SFWMD’s Phase I of model evaluation was completed in 2002 and was intended to help provide a basis for further development and application of a

hydrodynamic model for the FBFKFS and other projects. Phase I was done under contract by J. Hammrick, of Tetra Tech, Inc. Numerical model grids were generated, a five-year calibration data set was synthesized (and incorporated into the Physical Sciences Team's Standard Data Set), and the performance of the model was evaluated. Simulations of water surface elevation, currents, and temperature were judged to be more than adequate for confidence in long-term prediction of these quantities. Using the observationally defined inflows and their associated observed salinity, the model tended to over predict salinity, particularly in the northeastern potion of Florida Bay. This over prediction seemed likely to be due to uncertainties in estimates of freshwater discharge, evaporation, or other boundary exchanges.

The Phase I final report is currently under review at the SFWMD. Based on past comments from the Physical Sciences Team, the Florida Bay Science Program Science Oversight Panel, the Feasibility Study's workshop Review Panel, and information gained from Phase I, a detailed work plan for Phase II is being written. This phase will consist of the completion of a validated interior Bay circulation model that will enable the SFWMD, the United States Army Corps of Engineers (USACE), and other partner agencies to evaluate potential restoration alternatives as part of the FBFKFS. The success of this model development and application will be highly dependent upon inputs from boundary models, including a regional oceanic hydrodynamic model (for the Gulf of Mexico and Atlantic boundaries) and a regional hydrologic model at the Everglades boundary.

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