Circulation and Exchange of Florida Bay and South Florida Coastal Waters

Interdisciplinary Coastal Ocean Observations in the Florida Keys National Marine Sanctuary with Real-time Data Links

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Introduction

The coastal waters of the Florida Keys National Marine Sanctuary (FKNMS), surrounding the Florida Keys and the Dry Tortugas, are located in the transition region of the Loop Current and the Florida Current. The Dry Tortugas play a dynamic role in supporting regional marine ecosystems. Larvae that are spawned from adult populations in the Tortugas are spread throughout the Keys and south Florida by a persistent system of currents and eddies that provide the retention and current pathways necessary for successful recruitment of both local and more-distant recruits, with larval stages ranging from hours for some coral species to up to a year for spiny lobster. In addition, upwellings and convergences of the current systems provide frontal regions with concentrated food supplies that increase larval growth rates.

The well-known snapper spawning grounds of the Dry Tortugas are located adjacent to a persistent recirculation feature known as the Tortugas Gyre (Fig. 1), which provides an important mechanism for larval retention and distribution throughout the Florida Reef Tract as the gyre moves slowly west (Lee et al. 2002).

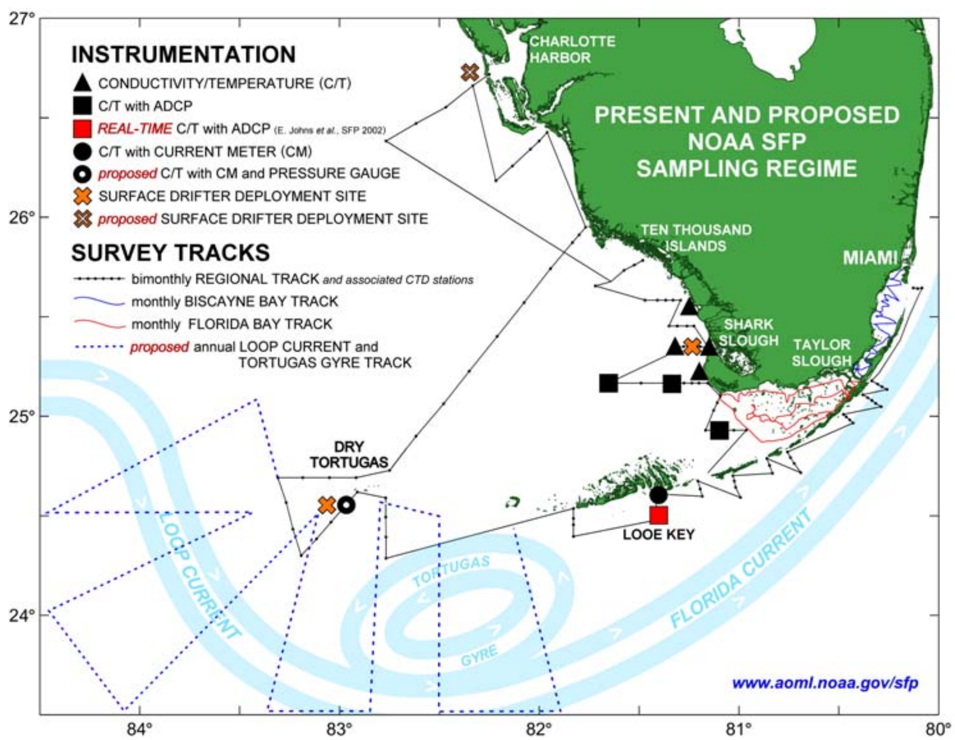


Figure 1. Instrumentation and survey tracks for present research program.

The protected spawning grounds of the Dry Tortugas are also affected by their proximity to the onshore edge of the Loop Current, which can deliver potentially harmful waters from remote land-based sources. A well-documented example of this occurred in 1993, when Mississippi River flood waters could be traced both in situ and by satellite as they were transported along the edge of the Loop Current, past the Dry Tortugas and the Florida Keys, and up the southeast U.S. coastline as far north as the Carolinas (Ortner et al. 1995).

Coral reefs of the FKNMS are subject to intrusions of potentially harmful waters from Florida Bay and the Southwest Florida Shelf because of their open connection to the Bay through Lower and Middle Keys passages. Surface drifters deployed on the southwestern Florida coast near the Shark River illustrate typical seasonal flow patterns (Fig. 2). Typically during the wet season (summer/fall), in response to prevailing winds, drifters tend to follow a westward path toward the Tortugas before entrainment in the Loop Current. During the dry season (winter/spring), drifters tend to travel southward across western Florida Bay and exit through passages of the Middle Keys. Subsequently drifters often remain in Hawk Channel near the reefs for several months, while at other times they reach the Florida Current and are quickly swept out of the area.

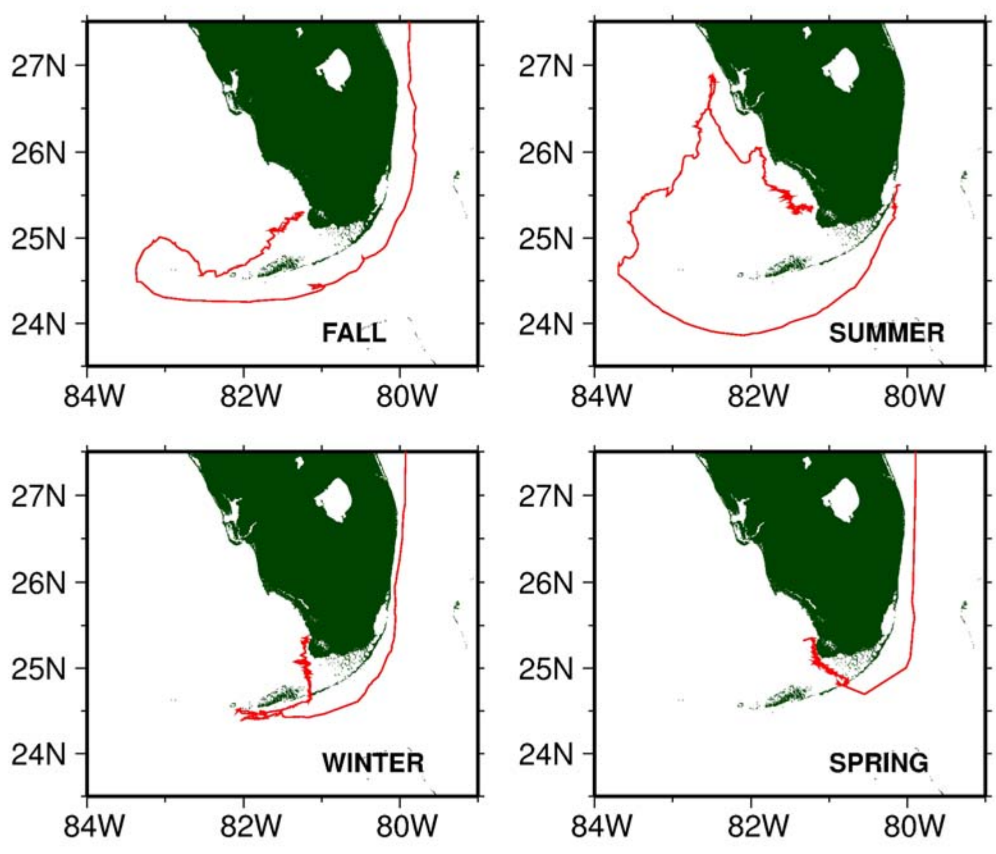


Figure 2. Representative seasonal satellite-tracked surface drifter trajectories (from Lee et al. 2002).

Keys passage outflow events occur sporadically, on time scales of days to weeks. Episodes of hypersalinity in Florida Bay, high turbidity, elevated nutrients, and harmful algal blooms such as red tides on the Southwest Florida Shelf can affect the health of reefs when these waters exit the

Bay. Because Florida Bay nutrient concentrations and turbidity are typically high compared to the oligotrophic conditions found offshore, the intrusions of Bay waters are thought to represent a potential threat to the health of the Florida Reef Tract (Porter et al. 1999).

Given such event-dominated variability, it is critical to resource management of the FKNMS and to the research community in general that these sustained, long-term, intrinsically linked current systems be measured continuously and the data made available in real-time wherever possible. Such information is needed to determine how current systems interact and transport materials between regions and what the potential ecological consequences may be. The value of real-time observations in the complex and interlinked marine systems of the south Florida region has already been shown during recent occurrences such as the “blackwater” event in winter 2002, the severe and persistent red tide bloom on the West Florida Shelf in spring 2003, and most recently by the transport of Mississippi River water into the FKNMS during May and June 2003. These data are also essential for the development, verification, and validation of numerical models being developed for Florida Bay and the surrounding coastal waters under the auspices of Florida Bay/Florida Keys Feasibility Study of the Comprehensive Everglades Restoration Plan.

Goals

The underlying goals of this research, funded by NOAA’s South Florida Program (SFP), are to obtain greater insight into the complex, coupled ecosystems of south Florida coastal waters, and to provide scientific support for resource managers of the FKNMS. Specifically these include the following:

- Observe and understand circulation in and around the FKNMS on tidal to interannual time scales.
- Observe and understand the role of the Loop Current in long-term variations of flow between the Gulf of Mexico and the Atlantic Ocean.
- Observe and understand the causes of physical/chemical/biological “event scale” variability.

The operational objectives of the research are to provide data necessary to address the above scientific goals, and to provide specific critical information needed by resource managers of the FKNMS for timely decision-making.

Methods

The measurement program in 2002-2003 continued the same basic elements used in previous years: bimonthly interdisciplinary shipboard surveys over the entire south Florida coastal system and detailed monthly interdisciplinary surveys of the interior of Florida Bay; satellite-tracked surface drifter releases at the mouth of the Shark River; and in situ moored measurements on the Southwest Florida Shelf and in the FKNMS. The geographic scope of the monthly surveys was expanded in 2002-2003 to include Biscayne Bay. In addition, a new one-day interdisciplinary hydrographic survey was added to the bimonthly surveys in the coastal waters surrounding the Dry Tortugas, and satellite-tracked surface drifter releases were initiated there in the vicinity of Riley’s Hump, an important larval spawning region (Fig. 1).

The bimonthly interdisciplinary surveys are conducted aboard the University of Miami’s research vessel *F. G. Walton Smith*, and the high-resolution monthly interdisciplinary surveys of

Florida and Biscayne Bays are conducted aboard the smaller research catamaran the *Virginia K* (Fig. 3).

Figure 3. Research vessels used for the bimonthly interdisciplinary cruises aboard the R/V *F. G. Walton Smith* (left panel) and monthly cruises aboard the R/V *Virginia K* (right panel) along the cruise tracks shown in Figure 1.

Along their ship tracks both research vessels continuously measure salinity, temperature, transmittance, chlorophyll_a (chl_a), and chromophoric dissolved organic matter (CDOM) fluorescence, and take surface water samples for phytoplankton pigments, cell counts, total suspended solids, and nutrient analyses. On station, both vessels obtain conductivity-temperature-depth (CTD) profiles, light transmission observations, and vertical profiles of chl_a fluorescence. There are 16 stations regularly occupied in Biscayne Bay, 40 stations in Florida Bay, and 99 stations in the surrounding coastal waters of the FKNMS and the Southwest Florida Shelf. Rosette or bottle casts are conducted for chemical and biological analyses and, at a subset of the stations, net tows for zooplankton are also obtained. In addition, both vessels are equipped with Acoustic Doppler Current Profilers (ADCP) that operate whenever conditions (primarily water depth and sea state) permit, yielding continuous observations of upper water column currents.

During the bimonthly cruises, surface drifters are deployed in the vicinity of the Shark River mouth and more recently also in the Dry Tortugas near Riley's Hump. These drifters are approximately 1 m tall, and are ballasted to float low in the water column. They are equipped with "sails" to allow the drifters to move with the water. The drifters are tracked by ARGOS satellite, and the series of fixes used to compute their speed and direction. Data from the satellite-tracked surface drifters (example shown in Fig. 4) are obtained in real-time and posted on NOAA's South Florida Program (SFP) web site at www.aoml.noaa.gov/sfp.

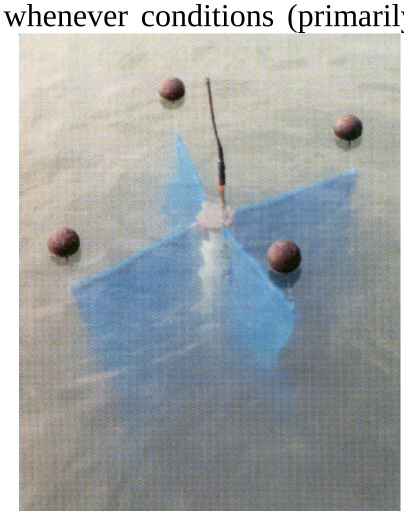


Figure 4. Surface drifter just after deployment.

Moored instruments are maintained in an array off the southwestern Florida coast and at the seaward edge of the reef tract at Looe Key, measuring temperature, salinity, and currents (Fig. 1). The Looe Key site has recently been upgraded to include real-time satellite communications for transmitting data to AOML. Additional sites in the Seven-Mile Bridge and Long Key Channelsare planned, and real-time communications and web-based data presentation methods are under development. This real-time observational network has been designed specifically as an early warning system for the FKNMS for intrusions of foreign water masses that could degrade FKNMS water quality or contain harmful algal blooms.

Findings to Date

Hydrographic Surveys

Variability in salinity, chlorophyll, and light transmittance occurs on a wide range of temporal and spatial scales, in response to both natural forcing such as wet/dry season precipitation and evaporation patterns and the interannual "El Niño" climate signal, as well as anthropogenic forcing such as water management practices in the south Florida canal system. Some recent examples of surface salinity variability are shown in Figures 5, 6, and 7. The full time series of surface property maps that have resulted from the bimonthly and monthly surveys are posted under Research Results on the SFP program web site at www.aoml.noaa.gov/sfp.

Figure 5 shows a contour map of surface salinity from data collected during a typical bimonthly survey of south Florida coastal waters. Data from the October 17-18 2002 monthly survey of Florida Bay have been incorporated into this map. While offshore waters of the Gulf of Mexico and the Florida Keys are relatively salty (35-36), the rainy season precipitation pattern has produced relatively freshwater discharges from rivers along the southwestern Florida coastline (30-33), and the salinity along the northern coastline of Florida Bay is fresher still (less than 25).

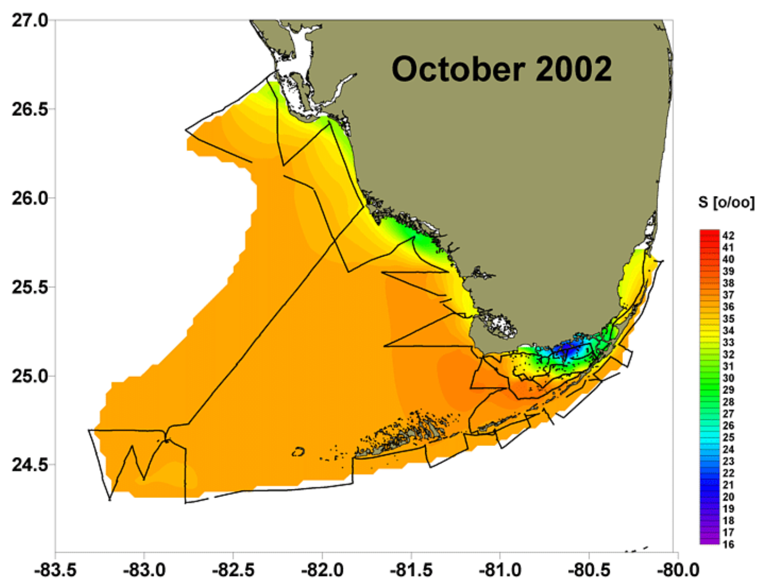
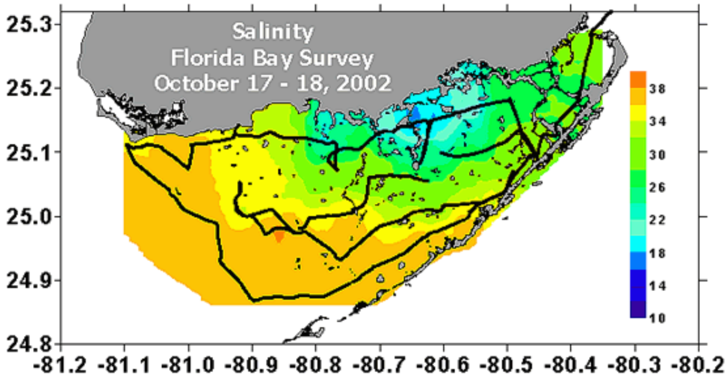


Figure 5. Surface salinity from the bimonthly cruise conducted during October 2002.

Figures 6 and 7 show contour maps of surface salinity from typical monthly surveys of Florida Bay and Biscayne Bay. The Florida Bay survey (Fig. 6) provides a closer look at the data also shown in Figure 5, showing the detailed cruise track that is designed to sample all accessible basins of Florida Bay over a two-day period. Most of the freshwater input at this time (October 17-18, 2002) is coming from the Taylor Slough area, in northeastern Florida Bay.



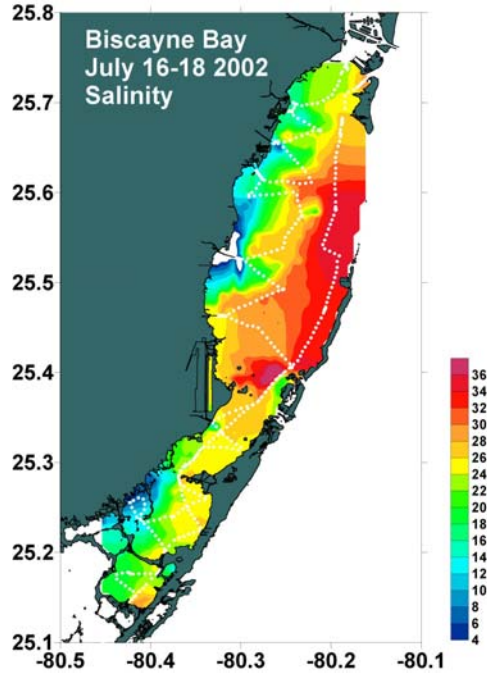


Figure 6 (above). Surface salinity in Florida Bay from monthly survey conducted on October 17-18, 2002.

Figure 7 (at right). Surface salinity in Biscayne Bay from monthly survey conducted on July 16-18, 2002.

The Biscayne Bay survey from July 16-18 2002 (Fig. 7) shows a typical wet season surface salinity pattern of high salinity (35-36) waters present along the western part of the Bay where there are open connections to the Atlantic Ocean, and very low salinity river and canal input (< 10) present at freshwater source locations along the northern shoreline of the Bay.

Surface Drifters

Satellite-tracked surface drifters can be used to track regional surface circulation patterns, which respond to large-scale forcing such as wind variability and sea level slopes. Some representative trajectories are shown below in Figures 8 and 9.

Figure 8 shows a drifter deployed near the mouth of the Shark River on December 10, 2003. This drifter moved slowly to the south until it ran aground just north of the Seven-Mile Bridge. This flow direction and speed, typical of the winter months, can carry harmful algal blooms such as red tides and black water, and riverine waters carrying high nitrate and phosphate loads, into close proximity to the waters of the FKNMS.

Figure 9 shows the trajectory of a drifter deployed in the Dry Tortugas on December 13, 2003. This pathway illustrates one of the perils that can potentially befall larval species, as the drifter almost immediately became entrained into the Loop Current/Florida Current/Gulf Stream and rapidly exited the area, reaching a latitude of 33^{o}N before becoming entrained in coastal currents of the Atlantic shelf.

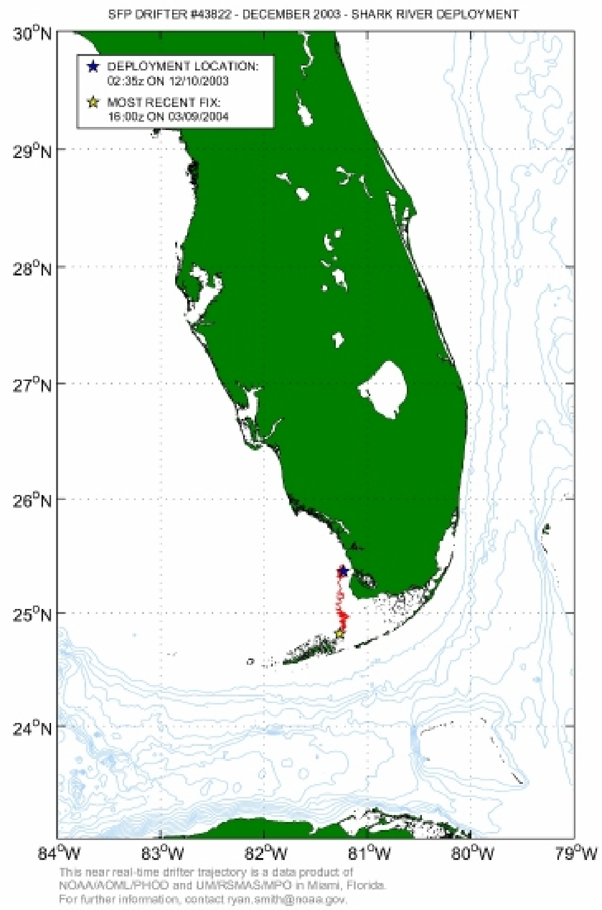


Figure 8. Surface drifter deployed on December 10, 2003, near the Shark River mouth.

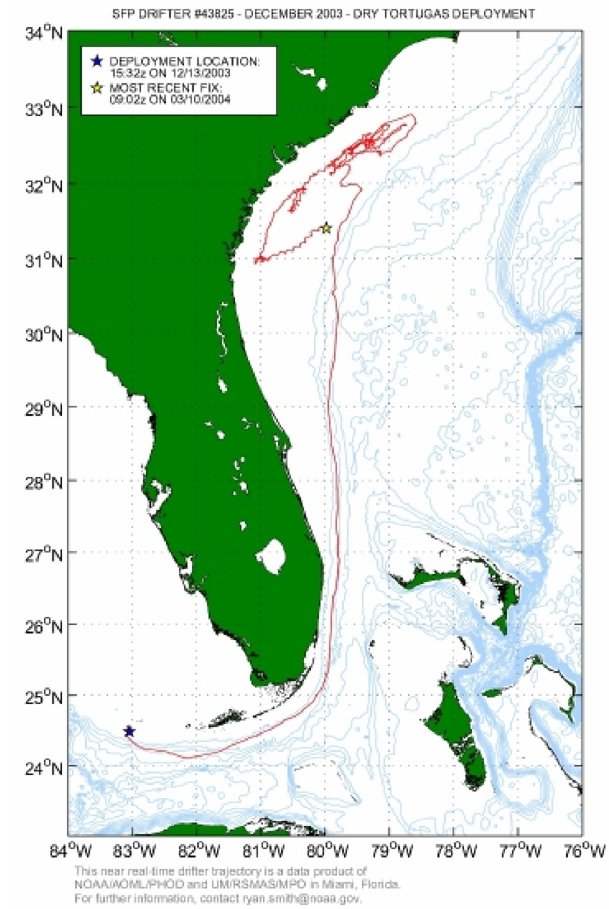


Figure 9. Surface drifter deployed on December 13, 2003, near Riley's Hump in the Dry Tortugas.

The Tortugas Gyre is a regional oceanographic feature that plays a particularly important role in larval transport and retention (Lee et al. 2002). This gyre, which is generally located to the south of the Dry Tortugas along the inshore front of the Loop Current, forms periodically over a period of weeks to months and then slowly drifts through the region until it is absorbed by the Florida Current offshore of the Keys. Figure 10 shows a satellite-tracked surface drifter that was deployed in the Tortugas in August 2002 during one of the bimonthly surveys. This

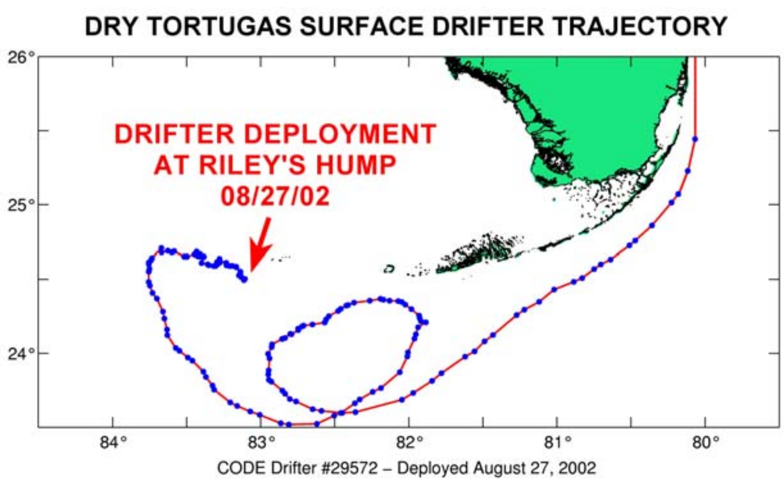


Figure 10. Trajectory of surface drifter deployed in the Dry Tortugas, August 2002.

drifter moved slowly to the northwest until it was entrained along the edge of the Loop Current, made one revolution around the Tortugas Gyre, and then exited the area via the Florida Current.

Florida Keys Passages

The Southwest Florida Shelf and the Atlantic side of the Florida Keys coastal zone are directly connected by passages between the islands of the Middle and Lower Keys. Movement of water between these regions depends on a combination of local wind-forced currents and gravity-driven transports through the passages, produced by cross-Key sea level differences on time scales of several days to weeks (Lee and Smith 2002; Smith and Lee 2003; Johns et al. 2003), which arise because of differences in physical characteristics (shape, orientation, and depth) of the shelf on either side of the Keys.

On long time scales, both the higher mean water level of the eastern Gulf of Mexico and variations in the strength and location of the Loop Current may have important influences on mean transports through Keys passages. The long-term mean volume transports through the primary channels of the Middle Keys are –55 m^3/s each for Channels 2 and 5, –260 m^3/s for Long Key Channel, and –370 m^3/s for the Seven-Mile Bridge Channel, where negative mean values represent outflows from Florida Bay (Fig. 11; Lee and Smith 2002). The Seven-Mile Bridge Channel accounts for about 50% of the flow, Long Key Channel for about 35%, and Channels 2 and 5 account for about 7% each. This southeastward mean flow provides a mechanism for direct transport from western Florida Bay, where the waters are known to undergo large changes in water quality, to the coral reefs of the FKNMS.

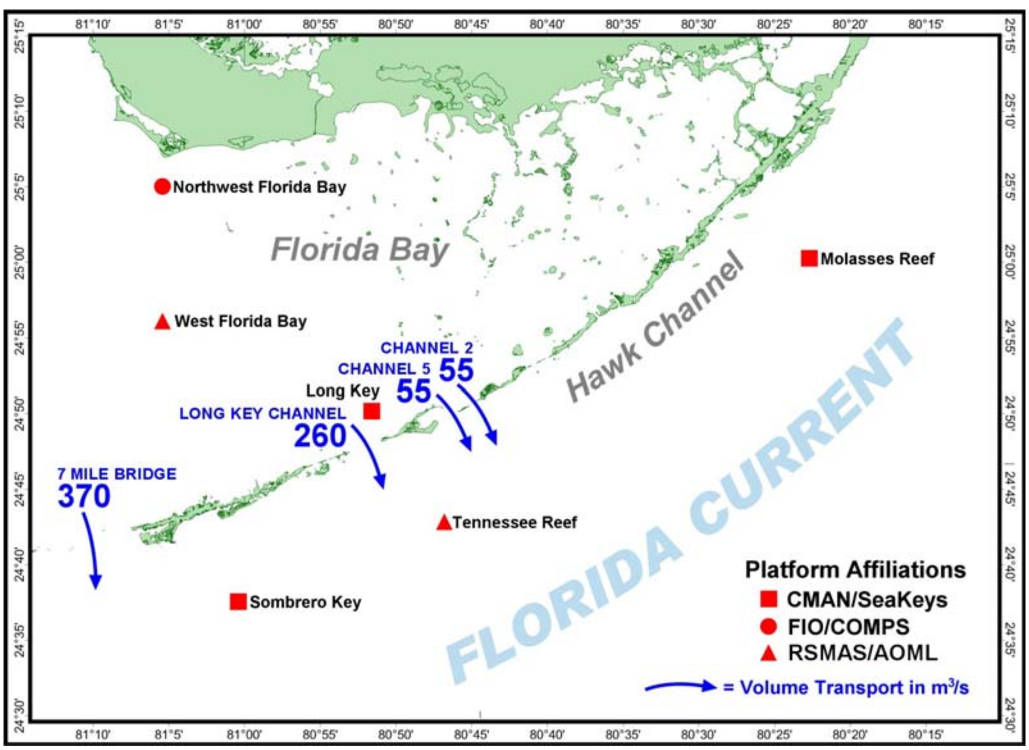


Figure 11. Long-term mean volume transport through the Keys passages.

Lee and Smith (2002) also found that there was an annual cycle of cross-Key sea level slopes and transports through Keys passages that had a direct relationship to the annual cycle of local wind forcing. Maximum subtidal outflows from Florida Bay occurred in the winter and spring following cold fronts, when winds from the west are more common. Minimum outflows and even flow reversals occurred in the fall when wind directions from the northeast and east prevail, causing several-day periods of inflow to Florida Bay from the Atlantic.

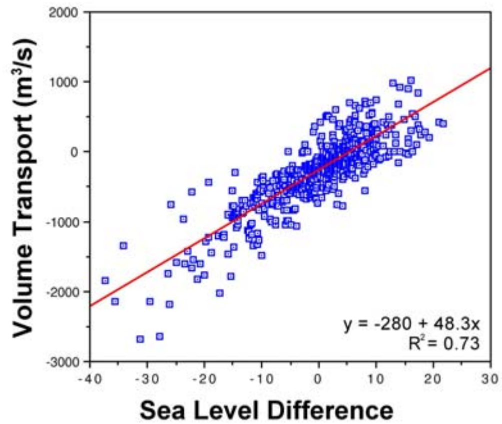


Figure 12. Volume transport vs. sea level difference (Tennessee Reef minus West Florida Bay).

Sea level differences across the Middle Keys are highly correlated with subtidal volume transport through Keys passages, as clearly shown from the comparison of bottom pressure measurements at Tennessee Reef and western Florida Bay, and shipboard volume transport observations (Fig. 12). Although reversing tidal currents dominate flows through Keys passages on shorter time scales, local wind forcing is the primary cause of this lower-frequency transport variability.

This situation is illustrated in another way in Figure 13 from Melo et al. (2003), using the network of tide gauges maintained by Everglades National Park (data courtesy of D. Smith). Winds blowing into Florida Bay from the west cause a gravity-driven outflow from Florida Bay due to a greater set-up of sea level in western Florida Bay than on the Atlantic side of the Keys (Fig. 13a). This is reversed for easterly winds, which push water out of Florida Bay and pile water up against the eastern margin of the Bay (Fig. 13b).

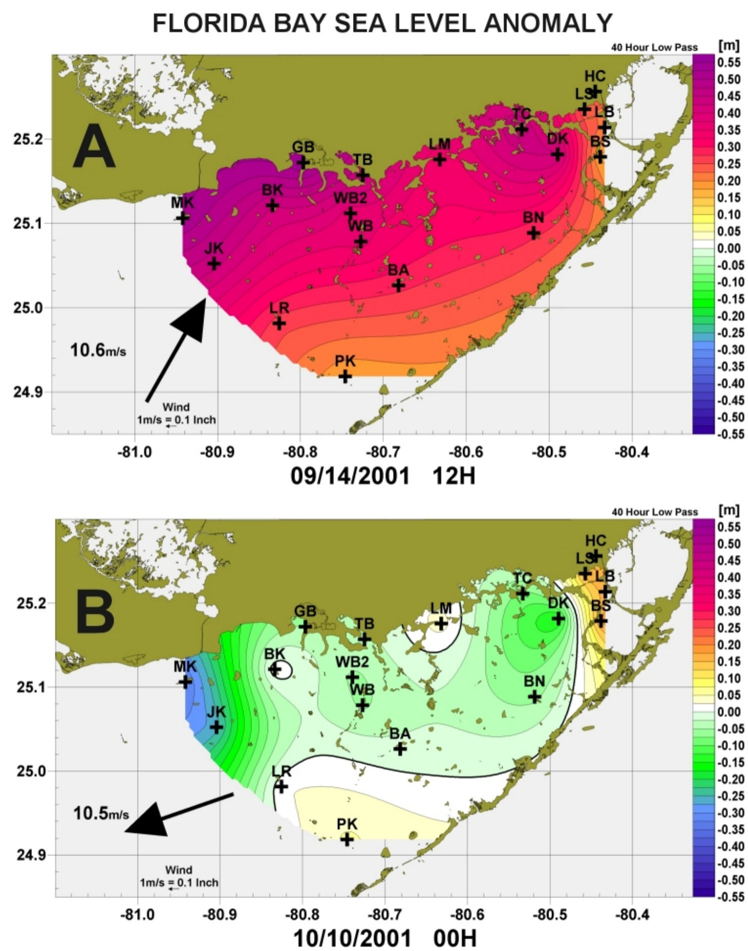


Figure 13. Sea level height in Florida Bay and its response to directional wind forcing (Melo et al. 2003).

These results have advanced our understanding of causes of circulation and water quality variability in Keys passages and the FKNMS. We are in the process of developing a real-time system for monitoring flow through major Keys passages. In this system, real-time sea level differences would be obtained from the CMAN/SEAKEYS stations at Long Key and Sombrero Key (Fig. 11). After an initial calibration phase involving intensive shipboard and moored data collection (an effort that is presently underway), the CMAN sea level data alone should provide calibrated volume transport information continuously and in real-time.

We used a prediction of outflow from Florida Bay to the reef made on the basis of the sea level difference to stage opportunistic field work during April 2003, which confirmed the outflow. Examination of SeaWiFS satellite images for this period showed that the outflow was unusually high in chlorophyll, and samples were obtained to ground-truth and calibrate the satellite data.

In addition to the Keys passages real-time volume transport observations, the Seven-Mile Bridge has recently been instrumented with conductivity-temperature (C/T) sensors, and soon will be instrumented with a fluorometer and a transmissometer. These instruments will be linked to AOML via cell phone to provide continuous real-time water quality information that, combined with the volume transport estimated from the sea level data, will yield a simultaneous record of volume transport and water quality from Florida Bay into Hawk Channel and the reef tract. Continuous water quality information will help to ground-truth satellite imagery and will be used to alert event-response teams who can provide rapid, targeted sampling in Keys passages, Hawk Channel, and coral reefs of the FKNMS.

Oceanographic Events

Some of the most dramatic oceanographic "events" that can affect marine environments of South Florida coastal waters happen only sporadically. In this context, the term "event" includes intermittent/irregular forcing functions such as remote intrusions; transient eddies and water releases; periodically enhanced outflows carrying high chlorophyll or nutrient levels from Florida Bay to the FKNMS reef tract; black water; red tides; and meteorological occurrences such as tropical storms. To adequately sample such events requires both the capability of near real-time recognition of these events, and the flexibility to rapidly stage targeted field sampling.

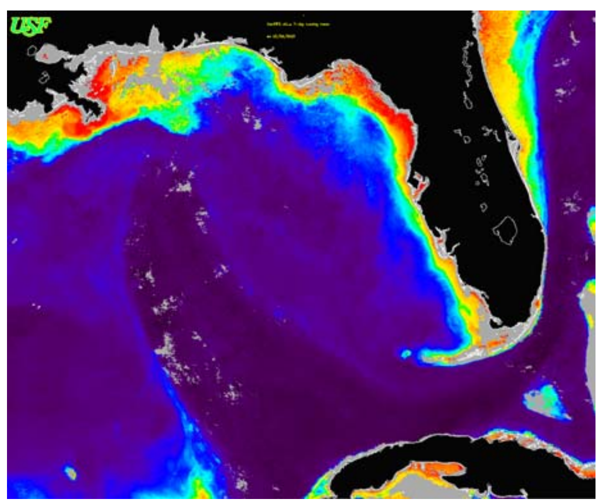


Figure 14. Satellite-derived ocean color image of the Loop Current/Mississippi River interaction, courtesy of C. Hu of the University of South Florida.

For example, in May-June 2003 Mississippi River water was transported to the Dry Tortugas region by the Loop Current as noted by satellite color images (Fig. 14) and HYCOM regional model results (Kourafalou 2003). This event was similar to a 1993 event documented by Ortner et al. (1995). Early notice enabled us to sample the properties of the anomalous water mass and to alert FKNMS managers and other interested researchers weeks prior to the Dry Tortugas incursion.

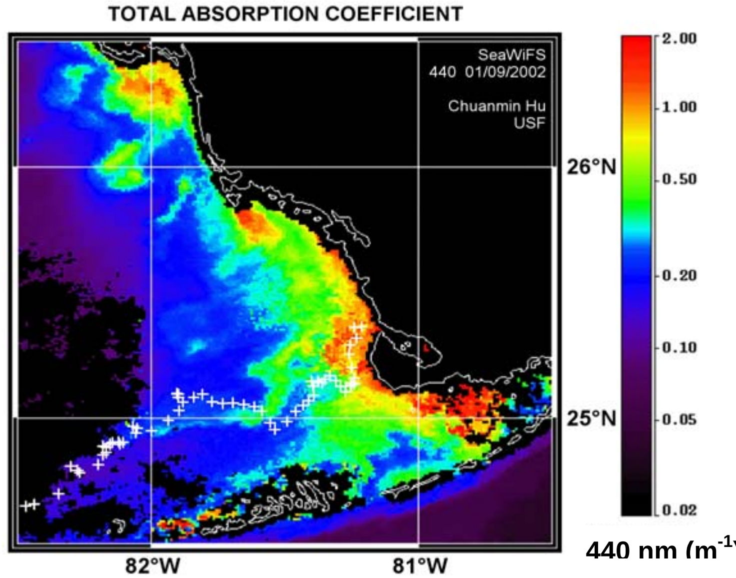


Figure 15. Total absorption at 440 nm (m^{-1}) from SeaWiFS, with superimposed surface drifter trajectory (+), January 2002 from Hu et al. (2003).

The advantage of using satellite data was clearly demonstrated during the spring 2002 "blackwater" event. During this episode, a large area of discolored water was noticed in the region of the Southwest Florida Shelf on SeaWiFs satellite color imagery. The dark area persisted for several months and moved slowly with the prevailing currents (SWFDOG 2002; Hu et al. 2003). We tracked what ultimately turned out to be an unusual diatom bloom with surface drifters deployed along the Southwest Florida Shelf, and staged additional event-sampling fieldwork in the FKNMS that proved helpful in confirming what was causing the discolored water. The drifter and satellite data were consistent (Fig. 15), and provided valuable information for studying the origin and fate of the anomalous water mass.

During the spring of 2003 a severe red tide bloom affected the Southwest Florida Shelf. While we were in the field conducting our regular April 2003 bimonthly survey we adapted our sampling strategy to aid the Florida Fish and Wildlife Research Institute in surveying the red tide bloom, and we deployed a satellite-tracked surface drifter in the bloom center. The trajectory indicated a slow circulation to the north along the mangrove shoreline that explained the concentration of the bloom around Cape Romano. The direction and slow speed of the currents may have contributed to the severity and longevity of this particular red tide episode.

Looe Key Mooring

The Looe Key long-term mooring site is located just seaward of the reef at 24°32.55'N, 81°24.13'W, in a water depth of approximately 22 m. This mooring (Fig. 16), a rigid spar buoy instrumented with temperature and conductivity sensors and a bottom-mounted Acoustic Doppler Current Profiler (ADCP) to measure currents, has recently been equipped with real-time communications. Data are communicated hourly to AOML using an MSAT satellite link, and are automatically posted onto the project web page at *www.looekeydata.net*, which also is accessible through the SFP program web site.

Figure 16. Looe Key real-time spar buoy.

Current and temperature measurements have been maintained at the Looe Key site for the past 13 years under various funding sources, making this the longest nearly continuous current measurement site in the Florida Keys. The site is important not only because of its close proximity to the popular Looe Key recreational diving area, but also because of its sensitive location downstream of Middle Keys passages where it is subject to transient outflows from western Florida Bay. Previous analyses of long-term current and temperature records from this site have shown the strong influence of Tortugas eddies as they move eastward through the region, as well as the influence of local wind forcing (Lee et al. 1992, 2002). Mean flows at this location are toward the west due to these combined forces, with a strong alongshore tendency. To understand longer-term ecosystem responses to this oceanographic and meteorological variability and to identify physical processes driving transient events and their frequency of occurrence requires continuation of these long-term measurements.

Figures 17a and 17b show salinity and temperature records from the Looe Key mooring for the period December 2002 to June 2003. The variability is striking and coherent, and is related not only to seasonal heating and cooling cycles but also to the location of Looe Key near the edge of the Florida Current. Periodically, warmer waters of that current are noticeable when it meanders onshore; transient outflow events from Florida Bay also can occur. Figure 17c shows surface currents recorded by the Looe Key Acoustic Doppler Current Profiler (ADCP). The variability is again striking, and is related to the location of the mooring site near the edge of the Florida Current. The predominant currents are oriented alongshore, alternately to the northwest or to the southeast, as the site is subject either to strong eastward Florida Current flow as it meanders onshore, or to the westward flows associated with eddies located along the current front (Fig. 1).

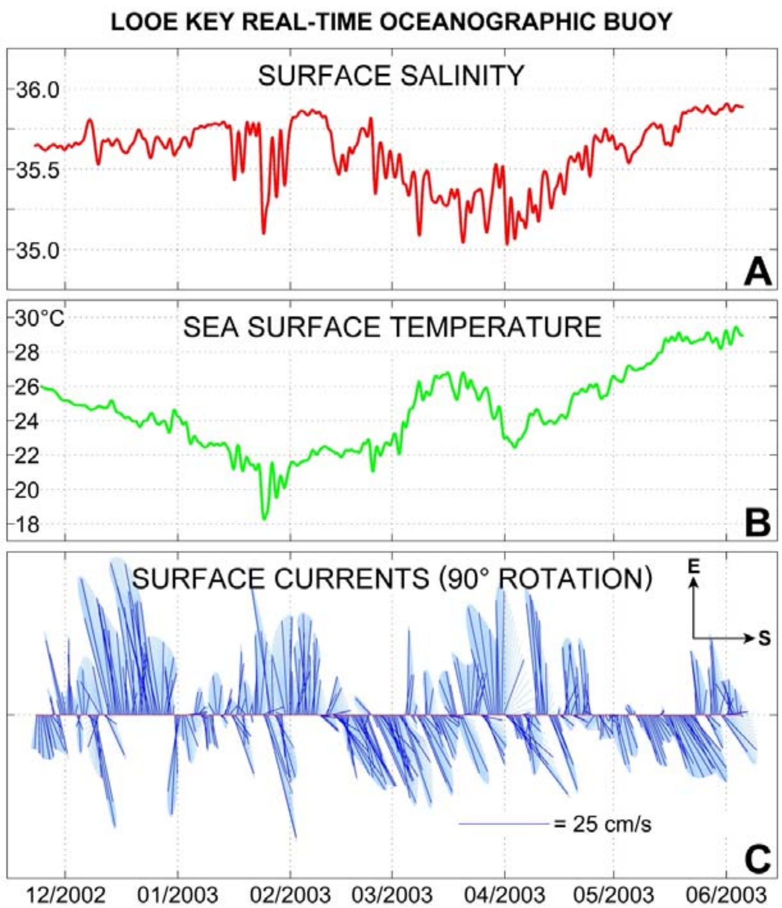


Figure 17. Time series of salinity (a), temperature (b), and currents (c) from Looe Key during the period December 2002 to June 2003.

Tortugas Region

A review of the state of knowledge of the currents and hydrography of the Tortugas region can be found in "Site Characterization for the Tortugas Region: Physical Oceanography and Recruitment" by Lee et al., posted at the FKNMS web site. This reference describes the oceanographic characteristics of the Tortugas using a synthesis of results from the literature as well as recent and ongoing studies. Particular emphasis is placed on the influence of physical processes on larval recruitment from local and remote sources, and the interconnectivity of the major regional current systems including the Loop Current, the Tortugas Gyre, and the wind-driven currents of both the Florida Keys coastal zone and the West Florida Shelf.

Given the recent awareness of the uniqueness and value of this nearly pristine coral reef ecosystem, which in fact helped lead to the creation in July 2001 of the Tortugas Ecological Reserve by the FKNMS to ensure its future protection, the need for a more complete understanding of the oceanography of the Dry Tortugas is pressing. The long-term monitoring program of bimonthly regional cruises recently added interdisciplinary, regional shipboard surveys of the Tortugas as well as regular satellite-tracked drifter releases at Riley's Hump, an important snapper spawning ground (Fig. 18).

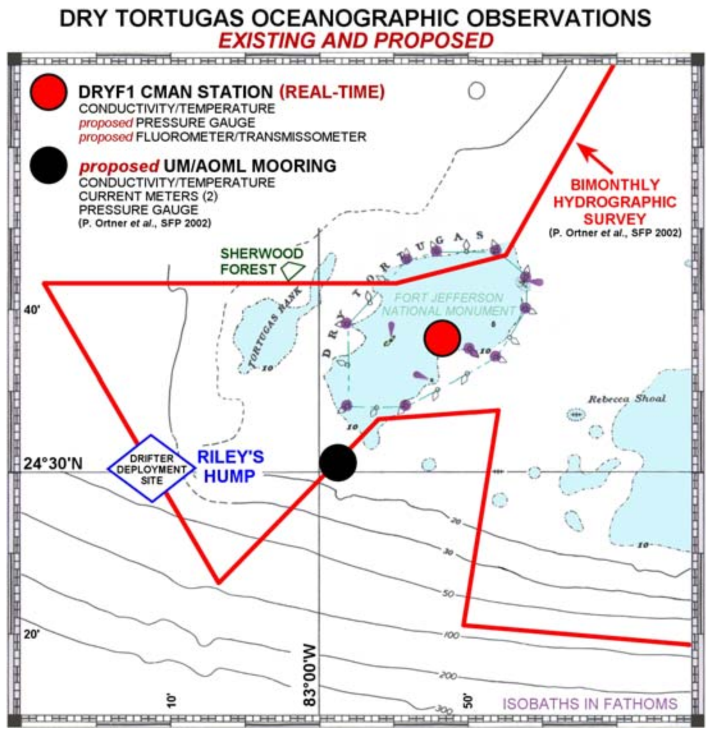


Figure 18. Existing and proposed oceanographic observations in the Dry Tortugas.

Future Plans

At this time our research in the FKNMS has been funded as part of SFP 2004 by NOAA's Coastal Ocean Program through March 2006. The bimonthly surveys aboard the R/V *F. G. Walton Smith* will be continued, as will the monthly surveys of Florida Bay and Biscayne Bay aboard the R/V *Virginia K.* Drifters will continue to be deployed in the Shark River mouth and the Dry Tortugas, and a third drifter deployment site will be added to the north near Charlotte Harbor.

The real-time effort will continue, with an emphasis on adding additional instrumentation to provide water quality information (i.e., fluorometer and transmissometer) as well as standard physical oceanographic parameters such as temperature, salinity, and currents. We are looking into the possibility of adding continuous real-time wave height observations to our suite of instruments located near coral reefs. We are also planning to expand the array, with stations in the planning stages for the Bear Cut Bridge near Virginia Key Beach in Biscayne Bay, and at the NOAA/National Undersea Research Center/University of North Carolina at Wilmington underwater laboratory, *Aquarius*, located at Conch Reef offshore of Key Largo.

Event sampling will continue to be a high priority, as will continued coordination with other federal, state, and local organizations to gain data that will lead to improved understanding of the causes and effects of marine environmental phenomena such as red tides, black water, and other events that require rapid staging of observational efforts.

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