Proceedings, OCEANS 2001 Conference
IEEE Oceanic Engineering Society & Marine Technology Society, Honolulu HI
November 5-8, 2001.

A Real Time Environmental Data Monitoring, Management and Analysis System for the Coral Reefs off the Coast of Belize†

Thomas B. Opishinski
Interactive Oceanographics, 81 Shippee Road, East Greenwich, RI 02818
iocean@surfree.com

Malcolm L. Spaulding
Department of Ocean Engineering, University of Rhode Island, Narragansett, RI, 02882
spaulding@oce.uri.edu

Klaus Rützler and Michael Carpenter
Caribbean Coral Reef Ecosystems, Department of Systematic Biology, Smithsonian Institution, Washington, D.C. 20560-0163

Abstract – In 1997 an oceanographic-meteorological monitoring, management, and analysis system was established (and upgraded in 2000) for the Smithsonian Institution's Caribbean Coral Reef Ecosystems program (CCRE) in Belize. The system, the first successful environmental monitoring system in coastal Belize, operates from the CCRE marine field station on Carrie Bow Cay. Many factors including operational environment, remote location, data accessibility, power restrictions, requirements for unattended operation and available communications for data transfer influenced system engineering design criteria. These considerations are discussed and supporting data and illustrations, demonstrating the reliability of the monitoring station and its importance to the research efforts of CCRE scientists, are provided. Descriptions of the various components that make up the system including an Internet data management and communication system, a data analysis and presentation system with embedded geographic information system, and a commercial environmental data acquisition system and sensors are provided.

I. INTRODUCTION

In 1972 scientists from the National Museum of Natural History (NMNH) of the Smithsonian Institution established a marine research laboratory in the Central American country of Belize [1]. Belize (formerly known as British Honduras) is situated south of Mexico's Yucatan Peninsula and is bordered by Mexico and Guatemala (Fig. 1). The marine laboratory was established on a 1-acre island, Carrie Bow Cay (Fig. 1 and 2), located 10 miles offshore on Belize's southern barrier reef, which is second in length only to Australia's Great Barrier Reef. Carrie Bow Cay was selected by NMNH scientists as a representative location to study reef ecology from dozens of potential sites around the Caribbean for its close proximity to the reef. Considered pristine, the barrier reef ecosystem offered researchers the highest diversity in reef structures, habitat types (coral reefs, mangrove swamps, sea grass communities, open-ocean and deep-sea floor) and animal and plant species. The Caribbean Coral Reef Ecosystems Program (CCRE), the umbrella program under which Carrie Bow Cay station has operated for 30 years, has supported hundreds of scientists and produced vital information for comparative studies with other reef ecosystems to assess biodiversity and to correlate environmental factors with biological phenomena and hazards (competition, parasitism, algal blooms, coral bleaching and invertebrate disease) [2]. Long-term measurements of environmental data useful in supporting these research efforts have, unfortunately, been limited to manual measurements of rainfall, air and water temperatures.

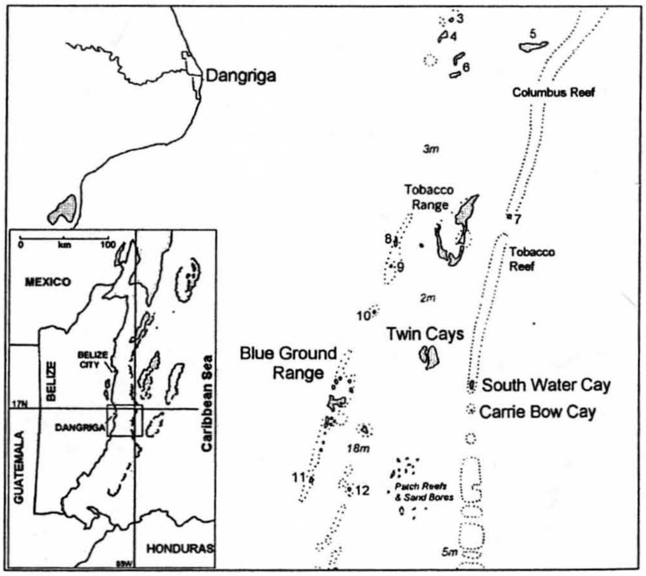

Fig. 1: Geographic location of Belize (inset), city of Dangriga, Carrie Bow Cay and other notable features. Extent of existing coral reefs are indicated by dotted lines

To address the fundamental need for reliable long-term oceanographic and meteorological measurements, design criteria for an environmental monitoring, management and analysis system were established in 1996 and activities to implement the system initiated. A system, based on the original requirements, began operation in the summer of 1997 but unfortunately was lost in a devastating fire that destroyed the Carrie Bow Cay research facilities in November 1997. A rebuilding effort ensued with improved facilities reopening for scientific research activities in 2001. As part of the rebuilding effort, a new environmental monitoring system (EMS) was designed and went into operation in September 2000. This paper focuses on the updated system installed in 2000 [3].

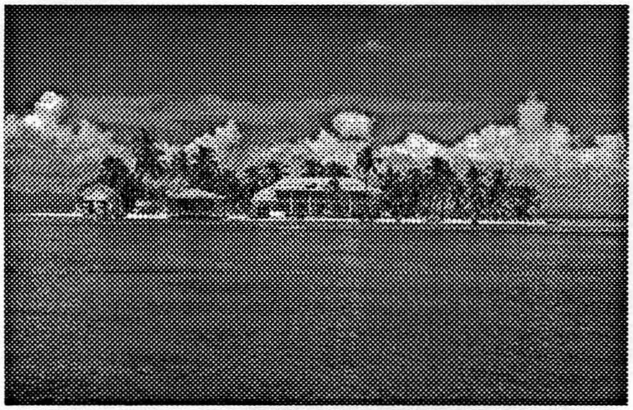

Fig. 2: The Smithsonian Institution's marine field station on Carrie Bow Cay viewed from the east. The Maya Mountains on the mainland are visible in the background. Photo courtesy of the Smithsonian Institution.

II. SYSTEM DESIGN CRITERIA

A basic criterion for the system was that it automates the acquisition process and allows easy access to the data. This appears to be a simple task except that "easy access to the data" was defined to include real time data access not only on Carrie Bow Cay in Belize, but also near or real time access at the Smithsonian Institution, Washington, DC. Data access, considered critical for monitoring system performance and determining maintenance requirements, was the driving force in the Carrie Bow Cay system design since electronic equipment requires vigilant maintenance due to the highly saline, tropical environment. Personnel trained to identify maintenance requirements are not always present on Carrie Bow Cay, and therefore, data availability at the Smithsonian Institution office in Washington, DC was considered a prerequisite. The task then, was to design and implement a low cost monitoring system that would reliably (and automatically) collect, archive, and transmit data from a remote Caribbean island (lacking modern communications) to Washington, DC. The overall system design, therefore, had to meet the following requirements.

The data acquisition system must be self-powered, reliable, permit real time access to the data measurements, be capable of operating multiple oceanographic and meteorological instruments in a tropical environment and allow for future expansion.

Data acquisition and archiving of the environmental information at the field site (Carrie Bow Cay) must be automated and continuous.

An automated data management and distribution system must be implemented in Belize to handle transmission of environmental information from Carrie Bow Cay to Washington, DC.

An analysis system must be implemented in Washington, DC that is capable of accessing, processing, and displaying the information once it reaches the Smithsonian Institution.

III. ENVIRONMENTAL MONITORING, MANAGEMENT AND DISTRIBUTION SYSTEM OVERVIEW

In 1997 an environmental data monitoring, analysis, and visualization system was established for Carrie Bow Cay. Upgraded in 2000, the EMS continually monitors real time meteorological (wind speed/direction, solar radiation, rain rate/accumulation, barometric pressure, air temperature, and relative humidity), oceanographic (water level, temperature, salinity, dissolved oxygen, pH, and turbidity), and system (internal) data (battery voltage and alarm) conditions. Measurements are taken every ten minutes.

Given the absence of modern communications on Carrie Bow Cay, and its remote location that precludes possible installation of affordable communication (telephone, Internet, or satellite), it was quickly apparent that transmission of environmental data from Carrie Bow Cay directly to the Smithsonian Institution's offices in Washington was not feasible. In 1997, Internet access had recently been established in the city of Dangriga, Belize and, although very few locations had a connection, the possibility of establishing a base station on the mainland to retrieve data from Carrie Bow Cay and upload it, via the Internet, existed.

As such, a preliminary design for the EMS consisting of three separate systems, separated geographically, but working together to accomplish the goals set forth in the system design criteria, was established. The first system, a field station on Carrie Bow Cay would collect, archive and transmit environmental data to a base station. It was preferred to locate an off-the-shelf data acquisition system with an integrated communication package to handle transmission between Carrie Bow Cay and Dangriga. A base station, established in the city of Dangriga (Fig. 1) on the Belize mainland (15 miles northwest of Carrie Bow Cay), would retrieve and archive data from the field station and transmit the data to Washington, DC via a common Internet protocol. A third system, operating on an Internet server at the Smithsonian Institution would receive the environmental data from the base station in Belize, process, archive and prepare it for access by Smithsonian staff.

Having determined the general architecture of the system, a commercial data acquisition system (an Endeco/YSI 6200 monitoring and data acquisition system) was selected for use on Carrie Bow Cay as the field site system. The 6200 system, responsible for performing the monitoring tasks, was selected from a number of available systems because it is powered by an integrated solar system, allows for future expansion, supports instrumentation capable of measuring the desired set of environmental parameters and can be configured for unattended acquisition and archiving. The 6200 data acquisition system offers an optional radio transceiver capable of transmitting data to a base station over short distances (10-15 miles) thus providing a mechanism to transmit data to the mainland. An R.M. Young wind monitor, tipping bucket rain gauge by Fluid Isolation Technology, pyranometer, temperature, barometric pressure and relative humidity probes form the suite of meteorological sensors integrated with the data acquisition system. Oceanographic instrumentation includes Endeco/YSI's 6820 multi-parameter water quality sensor with dissolved oxygen, turbidity, pH, conductivity, temperature, and pressure probes. A laptop computer, connected via a serial port to the 6200, archives and displays the environmental data before transmission to the base station.

The base station, through the generous cooperation of Naturalight Productions Ltd. (a company devoted to website creation and hosting), was established in Dangriga. The site at Naturalight Productions Ltd. offers an air-conditioned environment (one of the few locations in Dangriga with air conditioning) and telephone connections. A radio transmitter (the counterpart to the Endeco 6200 system on Carrie Bow Cay), a personal computer (PC) and antenna (mounted on the roof of the two story building) form the components of the base station system. Transmission of environmental data from Carrie Bow Cay is handled by the Endeco system. Once data reaches the base station it is archived on the PC hard drive. A dial-up Internet connection was installed at the base station site but, due to the high cost of maintaining the connection full time, it was decided that data would be transmitted to Washington, DC at regularly scheduled intervals rather than in real time.

An Internet Data Management and Communication System (IDMCS) was custom designed for operation at the base station in Dangriga and tasked to handle unattended data transfers from the base station to the Smithsonian Institution in Washington, DC. The IDMCS monitors operational status of the base station operations and environmental data transmissions from Carrie Bow Cay with event information stored in an activity log. The IDMCS is configured to connect and log itself onto the Internet, using the dial-up Internet connection, at a predetermined time each night. Once the Internet connection is established the IDMCS connects to the Smithsonian Institution server, logs in and then uploads any new data received since the last Internet transfer. The activity log is also uploaded to provide additional information for diagnosing system operations. Although the Internet data management and communication system can be configured to upload data in (near) real time, costs for Internet access are kept to a minimum by limiting access for data uploads to fifteen minutes each day. In this manner, the total monthly access time does not exceed 465 minutes per month (for a 31 day month). The cost of Internet access is therefore limited to the basic fee, which permits eight hours access time per month. Information transmitted to the Smithsonian Institution is sufficient to identify a problem or failure of individual measurement probes at the field station or a failure in data communications within 24 hours of the occurrence.

Unattended operation of the base station required careful consideration in the design of the Internet Data Management and Communications System. In the combined 1-year history of operation (1997 and 2000/2001) the system has been subjected to regular power and telephone outages, Internet access problems during peak use hours on weekends, Internet timeouts, poor quality connections, and failed connections. To avoid data loss during Internet failures the system monitors the Internet connection during uploads. In the event of an Internet failure, necessary actions are taken to reset the system and prepare the data to be uploaded during the next day's transmission. In this manner the activity log and data are updated on the Smithsonian Institution server in Washington, DC when the next successful Internet connection is made. Data loss is avoided by the system since archives are maintained at the field and base stations and on the Smithsonian Institution's server.

The Internet Data Management and Communication System maintains continuous automatic operation of the base system, even in the case of power outages. Once power is restored after an outage, the IDMCS will start all software necessary to operate the system during the system reboot. An uninterruptible power supply and surge protector hardware protect the PC and radio transmitter during brownouts and power outages.

At the National Museum of Natural History in Washington, DC, scientists managing the CCRE program have access to the uploaded environmental data using the IDMCS. The IDMCS, operating independently on any number of computer workstations, downloads the data from the Smithsonian Institution server after it is uploaded from the base station in Belize. Since data access is gained via the Smithsonian Institution server, worldwide access to the environmental data is available to the scientists at any location where an Internet connection can be established. In addition, the IDMCS can be configured to further distribute the data to alternate servers.

COASTMAP, an environmental monitoring, modeling and management system designed by University of Rhode Island Ocean Engineering scientists and offered commercially by Applied Science Associates (Narragansett, RI) was utilized to provide scientists with tools for data visualization and analysis [4]. COASTMAP features an embedded geographic information system (GIS), environmental data analysis (e.g. time series analysis including statistical and power spectral, filtering, and harmonic analysis) and presentation tools (e.g., real time status board and scientific graphing utility). COASTMAP has the capability to collect data directly with conventional instrumentation or in conjunction with real time monitoring systems using cell phone communications, radio/satellite telemetry, Internet or combinations of these protocols (as in the present case). COASTMAP may also be configured to include optional environmental models (e.g., three-dimensional hydrodynamics and particle based pollutant transport) to hindcast, nowcast or forecast the dynamics in the operational area with real time data assimilated, used as boundary condition forcing for the models or used to calibrate model predictions [5].

IV. SYSTEM INSTALLATION

Installation of the (new) system began in September 2000 and was completed in February 2001. Figure 3 details the location of the acquisition system and sensors that make up the field station on Carrie Bow Cay. The 6820 water quality sensor is mounted at the end of the boat dock (western side of the island) in a stilling tube at a depth of 2.5 feet (Fig. 4). This location was selected because it offered easy mounting and access to the instrument from the dock, the communication cable could be strung along the underside of the dock for protection, and it is in open water. The water quality sensor is connected by a 250-foot cable that runs the length of the dock, then through underground PVC pipe to the main building to the 6200 data acquisition system. The 6200 data acquisition system, located in a second story storage room in the main building, is also connected to a tipping bucket rain gauge and meteorological instrumentation (wind monitor, pyranometer, barometer, and temperature and relative humidity probes), solar panels, radio communications antenna and lightning protection equipment mounted on a twenty-foot aluminum tower (Glenn Martin Engineering). To avoid impact from trees and other wind obstructions on the measurements, the rain gauge was mounted on the eastern edge of the roof.

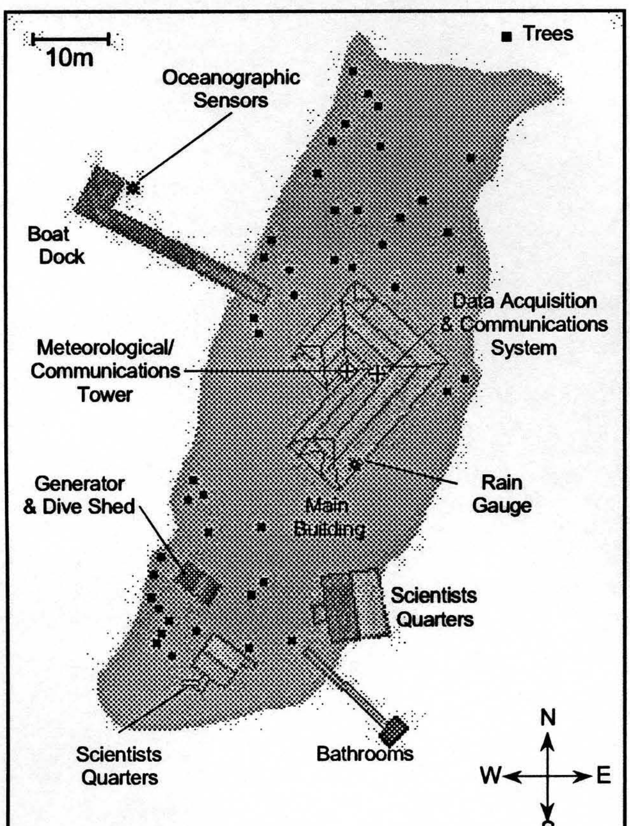

Fig. 3: Carrie Bow Cay Marine Field Station. Locations of structures, environmental monitoring system components and trees are identified.

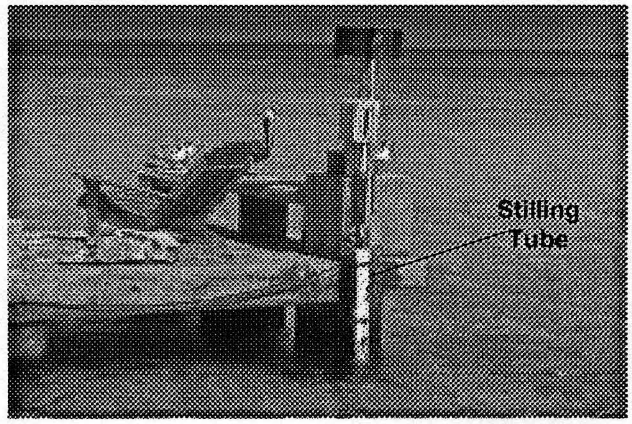

Fig. 4: Stilling tube mounted to end of boat dock that contains the Endeco 6820 Water Quality Sensor.

A platform was constructed between the second story porches on the southern facing side of the main building for mounting the tower. Due to strong local trade winds and frequent storms the platform (Fig. 5) was constructed from 2 by 8 inch wood beams and secured to the building's main support posts with 8-inch lag bolts. Truss hangers and lag bolts were used to secure the platform crossbeams with stainless steel bolts securing the tower's support feet to the platform.

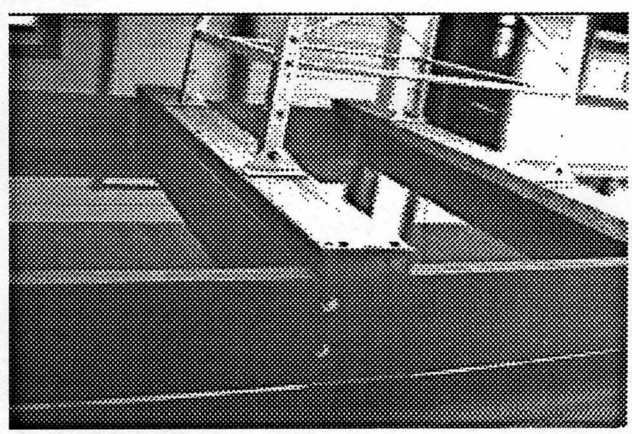

Fig. 5: Platform constructed to support the 20-foot aluminum tower. Base of tower is shown resting on the platform but is not yet bolted to the platform.

Mounting the tower on the second story platform provided many advantages. First, the wind monitor was mounted at the top of the tower such that wind speed and direction were measured at the meteorological standard height of 10 meters. The antenna, also mounted near the top of the tower, was required to face Dangriga on the mainland (to the northwest). To provide a clear line of site for radio communications between the field station and the base station along this path (The transmission path is partially obstructed by palm trees on Carrie Bow Cay and on Twin Cays.), the antenna was mounted near the top of the tower. The pyranometer was also mounted on the tower at a height sufficient to eliminate shading of the sensor.

Easy access to the sensors, cables and connectors for servicing and cleaning was also a consideration. The tower, which is designed for climbing, allows one to reach the antenna, solar panels and pyranometer. Access to the tower is gained from the second story porch without the need for a ladder. To reach the meteorological instruments at the top of the mast the tower may be rotated about two of its mounting feet and lowered to a horizontal position where meteorological instruments can be reached directly from the second story porch (Fig. 6). To permit rotation, the tower was placed in a position, after careful measurement of the tower dimensions, to provide a clearance of 1-inch from the gutters that extend from either side of the porch roofs. Clearance is maintained both in the tower's vertical position and while lowered to a horizontal position. Sensor, support arms and antenna were mounted and oriented on the tower to permit sufficient clearance when the tower is raised and lowered.

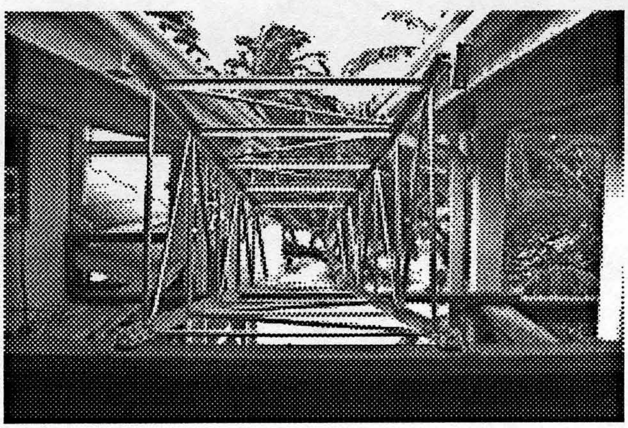

Fig. 6: Tower shown in horizontal servicing position. At this point of the installation, the lower half of the tower is attached to the platform as an exercise designed to verify that sufficient clearance is available between the roof and tower during rotation.

To prevent rubbing and chaffing of cables, the instrument, antenna and lightning ground cables were secured to the mast and tower with cable ties and protected with additional layers of electrical tape where they passed over the tower frame. Cable runs, along the length of the tower, were separated with the power cable from the solar panel on the left, data and antenna cable along the center and antenna lightning arrestor cable on the right (Fig. 7). All connectors, nuts and bolts are coated with Dow Corning Aircraft Silicone Sealant to protect against corrosion due to the highly saline environment.

Figures 8, 9 and 10 show the tower after the installation was completed. The photograph shown in Fig. 8, taken from beneath the tower, illustrates the limited clearance that was available between the tower and gutters. Figure 9 shows the tipping bucket rain gauge (foreground) and the instrument tower in the background. The side arm, on which the pyranometer is mounted, is visible in Fig. 9. The radio antenna is visible in Fig. 10.

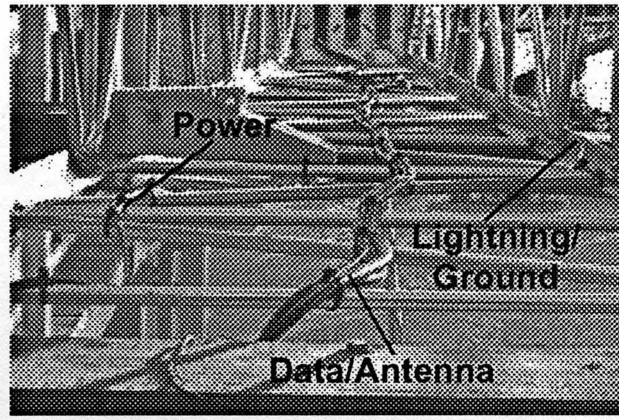

Fig. 7: Cable runs separated by type – power (left), data and antenna cable (center), and lightning ground cable (right).

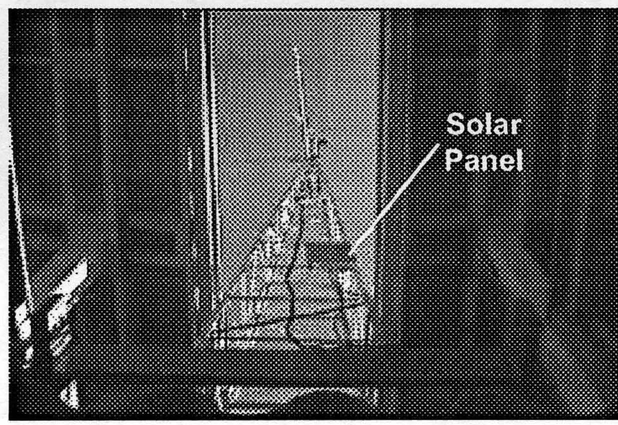

Fig. 8: Standing on the ground looking upward at the instrument and communications tower. The location of the solar panel used to power the system is indicated.

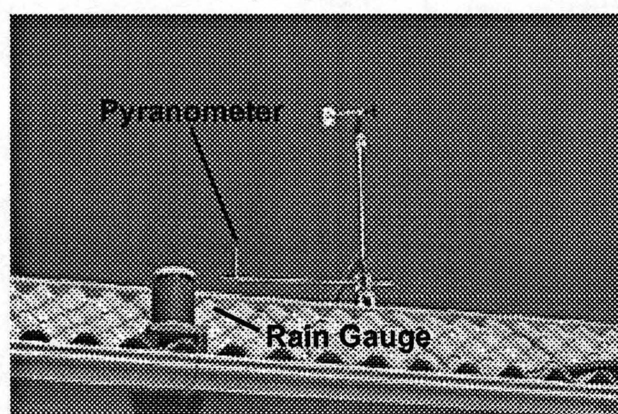

Fig. 9: View of tower and tipping bucket rain gauge as viewed from the east.

Fig. 10: Meteorological and communications tower viewed from the south.

V. THE SYSTEM IN OPERATION

On Sept 17, 2000 at 14:30 the environmental monitoring system at Carrie Bow Cay began operations with the first upload of data to the Smithsonian Institution occurring at 23:55. During the first three weeks of operation, mother nature provide two durability tests of the system in the form two strong "Northers" (local reference to fast moving thunder storms that are common during late summer and early fall) on September 19 and 20 and Hurricane Keith whose effects were observed from September 28 to October 6. Responsible for 19 deaths, Hurricane Keith generated maximum winds of 140 mph with torrential rains causing flooding in many coastal areas of Belize and Mexico. Figures 11 and 12 show the satellite and radar images (Courtesy of WSI Corporation), respectively, for October 1.

Before hurricane struck the area on October 1, the island was evacuated since previous experience had shown that it was often overrun by tidal surge during hurricanes (maximum elevation on the island is approximately 1 meter). The center of the hurricane passed approximately 40 miles to the north of Carrie Bow Cay while moving slowly to the west. As it neared the coast of Belize it stalled and did not resume passage across the Yucatan Peninsula until October 2. Major damage resulted in areas lying in the path traveled by the hurricane's eye including Belize City and many of the cays offshore northern Belize. The monitoring and communication system survived the storm, although a power outage on the mainland precluded the occurrence of the October 2 Internet transfer, data uploaded at midnight of October 1 provided reassurance that the island had not been swept away.

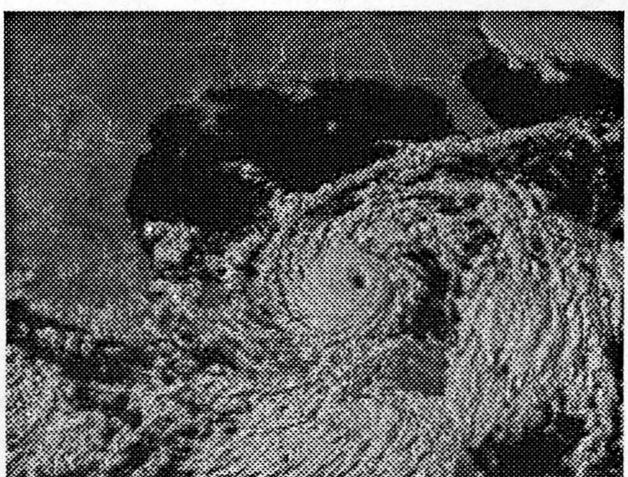

Fig. 11: Satellite image of Hurricane Keith on October 1 at 17:30 GMT.

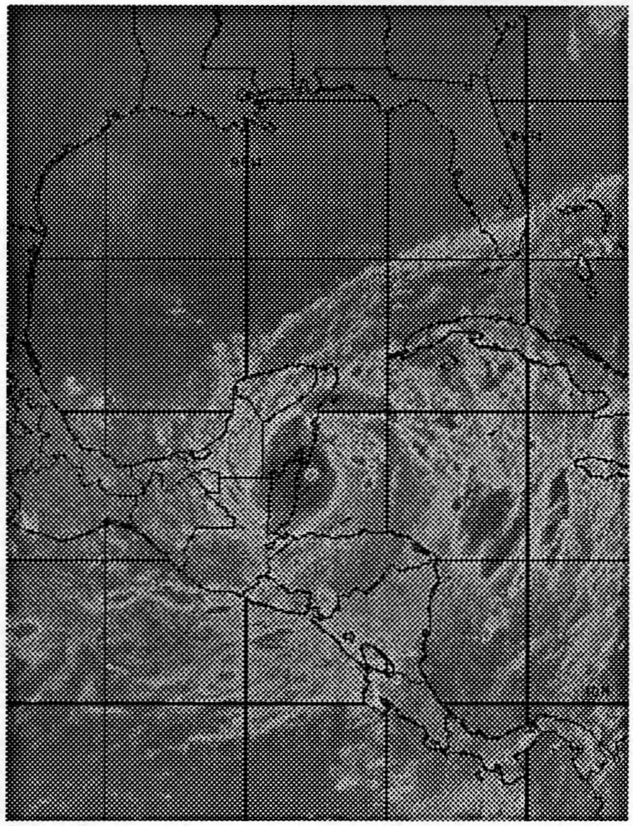

Fig. 12: Radar image of Hurricane Keith on October 1 at 17:30

Initial indication that conditions south of Belize City were less severe than reported came from data uploaded at midnight on October 1 by the environmental monitoring system. As the storm approached along a path carrying it north of Carrie Bow Cay the winds began to blow from the west. This probably had two effects on local conditions: 1) it limited the tidal surge in the area as the wind tended to push the water offshore into the oncoming surge; and 2) wind speeds were reduced due to the presence of the Maya Mountains that stretch from central Belize southward. Confirmation of mild conditions around Dangriga came by telephone from the proprietor of Naturalight Productions who had also been monitoring conditions on the island from the base station on the afternoon of the 2nd before a power outage shut down the computer and radio. After power was restored in Dangriga early on October 3rd, communications between the base station and field station resumed providing assurance to those who had evacuated that little damage had occurred on the island.

Selected meteorological records (wind speed/direction, barometric pressure and daily precipitation) on Carrie Bow Cay are shown in Fig. 13 for the period from September 19 to October 8. In this figure the change in wind direction caused by the hurricane is clearly shown beginning on September 29 and the resulting wind speed (each sample averaged over 90 seconds) rarely exceeds 15m/s (33.5mph). Total rainfall for October 1 and 2 approached 5 inches leading to a sharp decrease in salinity (Fig. 14). Figure 14 also details surface elevation and dissolved oxygen records for the same time period as Fig. 13. Daily oxygen cycles are disrupted from the 30th of September to the 3rd of October by the hurricane while the water level record shows a substantial disruption to the normal tidally dominated pattern.

Evidence of the two "Northers" occurring on September 19 and 20 is shown primarily in the wind speed and rainfall records. Although short in duration, these storms can be quite intensive as shown by the wind speed of the first storm, which exceeded observed wind speeds during the hurricane. While the first "Norther" had stronger winds than the second, it had less intense precipitation than the second storm. As a result there was little to no change in the salinity observed after the first storm. A sudden decrease in salinity was observed after the second storm and, after the salinity begins to recover, a second drop in salinity was observed.

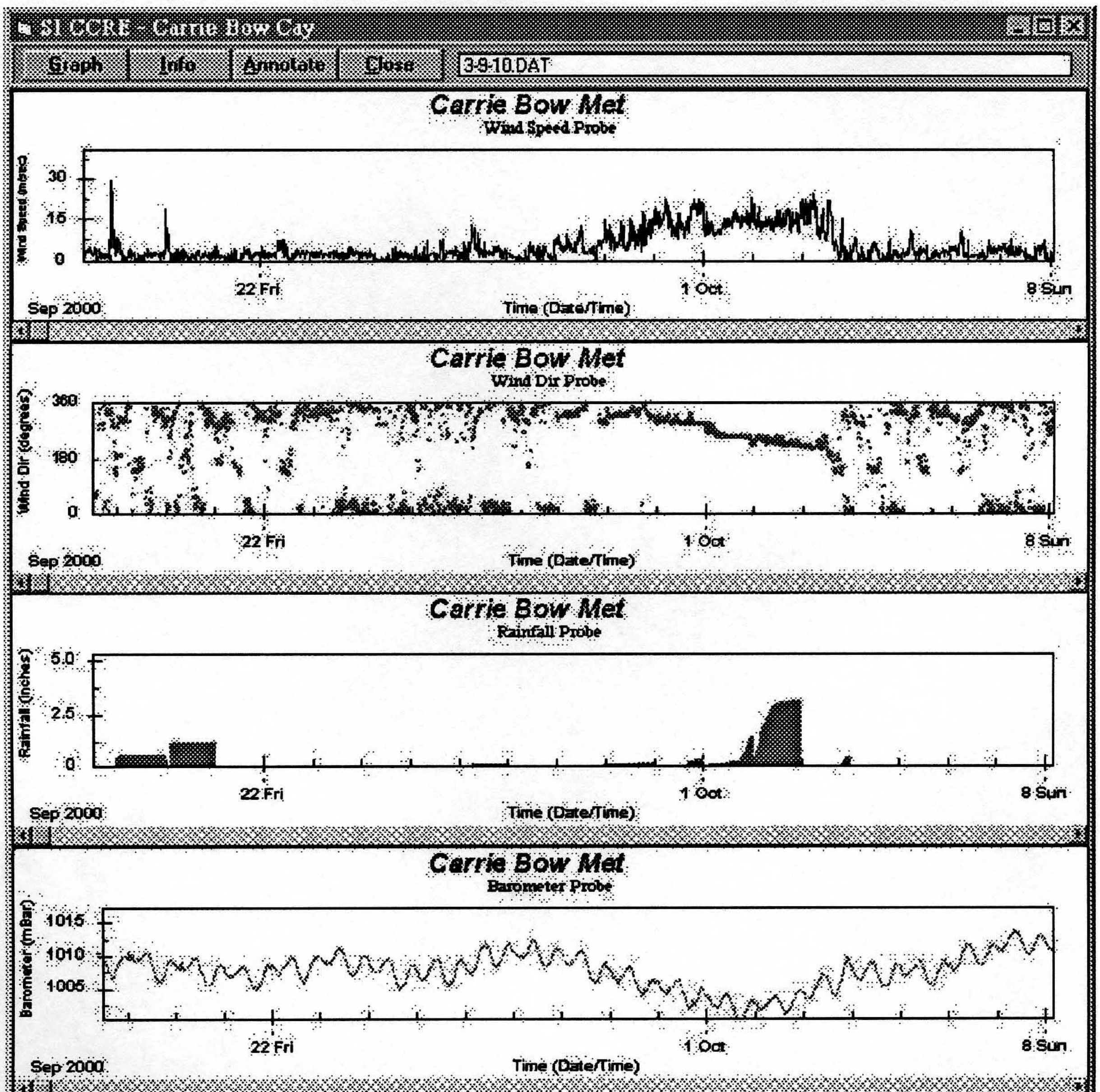

Fig. 13: Meteorological conditions on Carrie Bow Cay (September 19 – October 8).

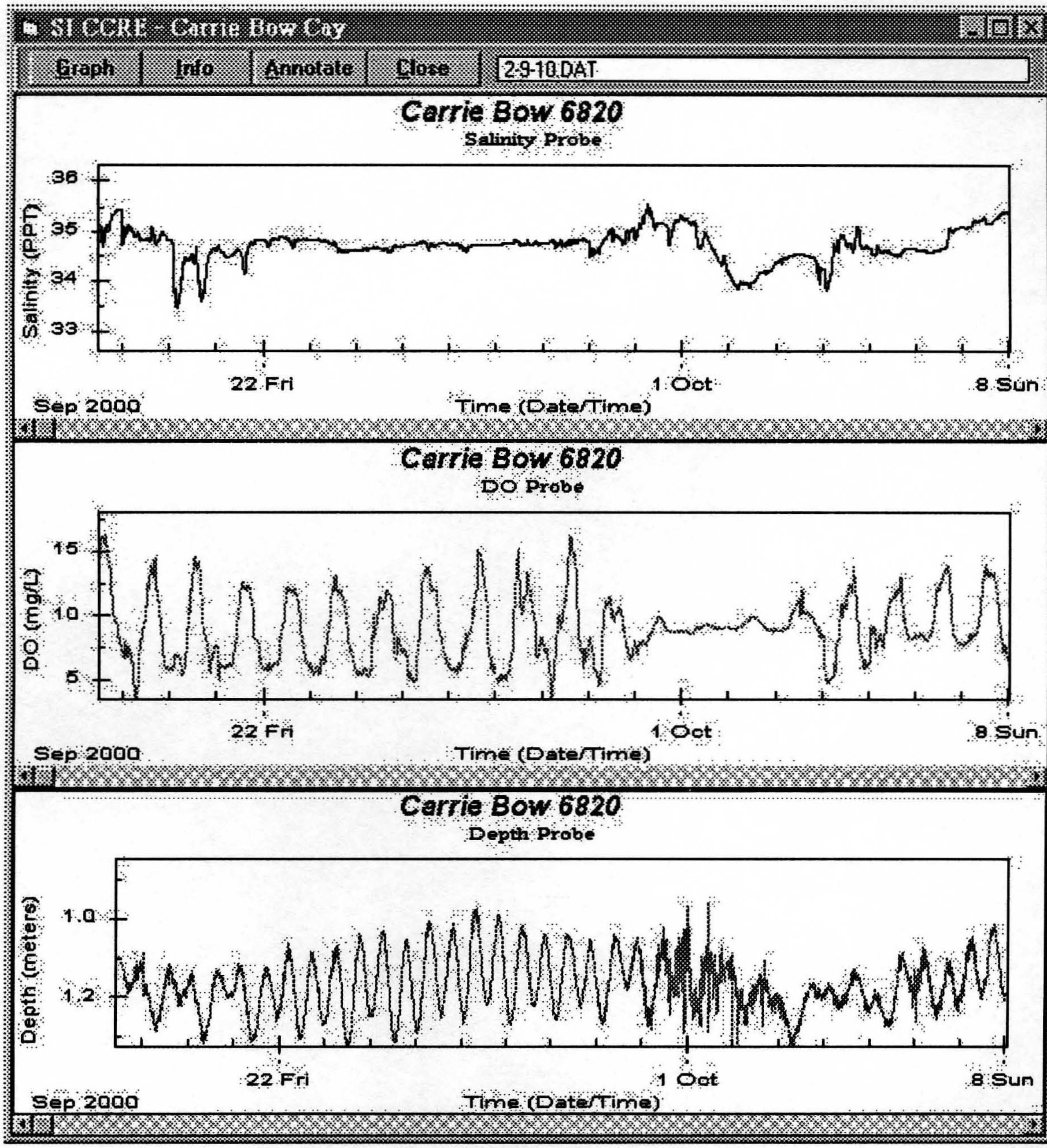

Fig. 14: Oceanographic conditions on Carrie Bow Cay (September 19 – October 8).

Having survived the passing of the hurricane the environmental monitoring system had demonstrated the importance of data accessibility while providing scientists with valuable data allowing them to examine the interactions of the various environmental parameters. To date, the system has operated continuously. With a routine maintenance program in place the objective is to generate long-term environmental records for the area.

COASTMAP, which provides access to historical data (e.g., Fig. 13 and 14), also provides a real time status board (Fig. 15) for displaying current conditions and additional tools to analyze data. For example, statistics and spectral content may be generated for any data set while water level measurements may be decomposed to calculate harmonic tidal constituents. Forecasts of tidal conditions may then be generated from the tidal constituents. As an example, Fig. 16 is a graph comparing a prediction, generated in February, of the tidal record for March 2001 with the actual water level measurements. For this exercise, the amplitudes and phases for the principal seventeen constituents were calculated by COASTMAP's harmonic decomposition utility.

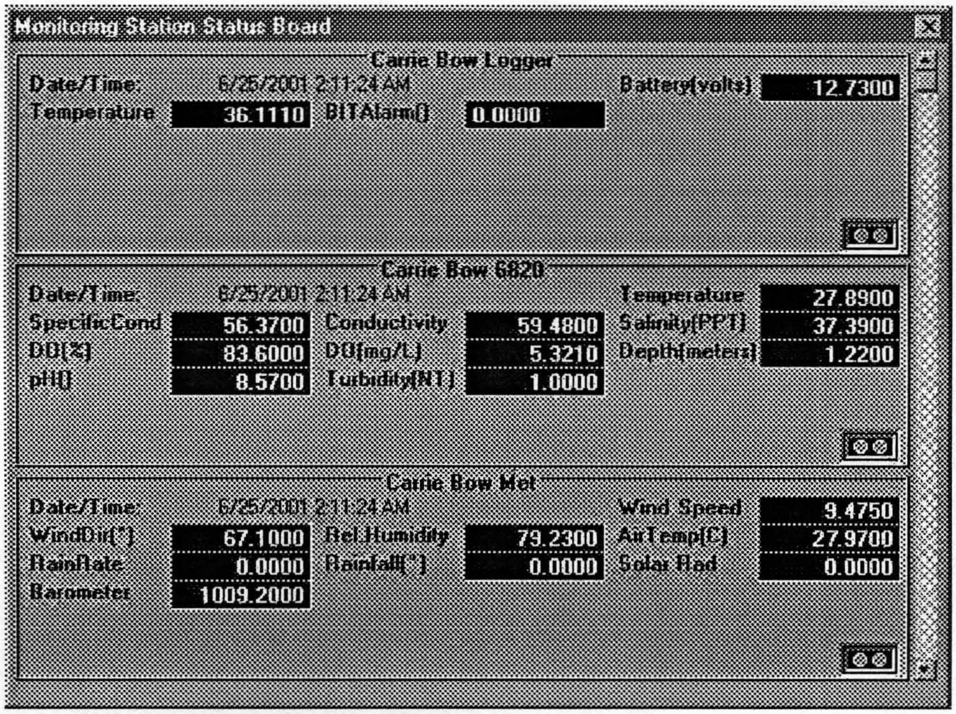

Fig. 15: COASTMAP's real time status display.

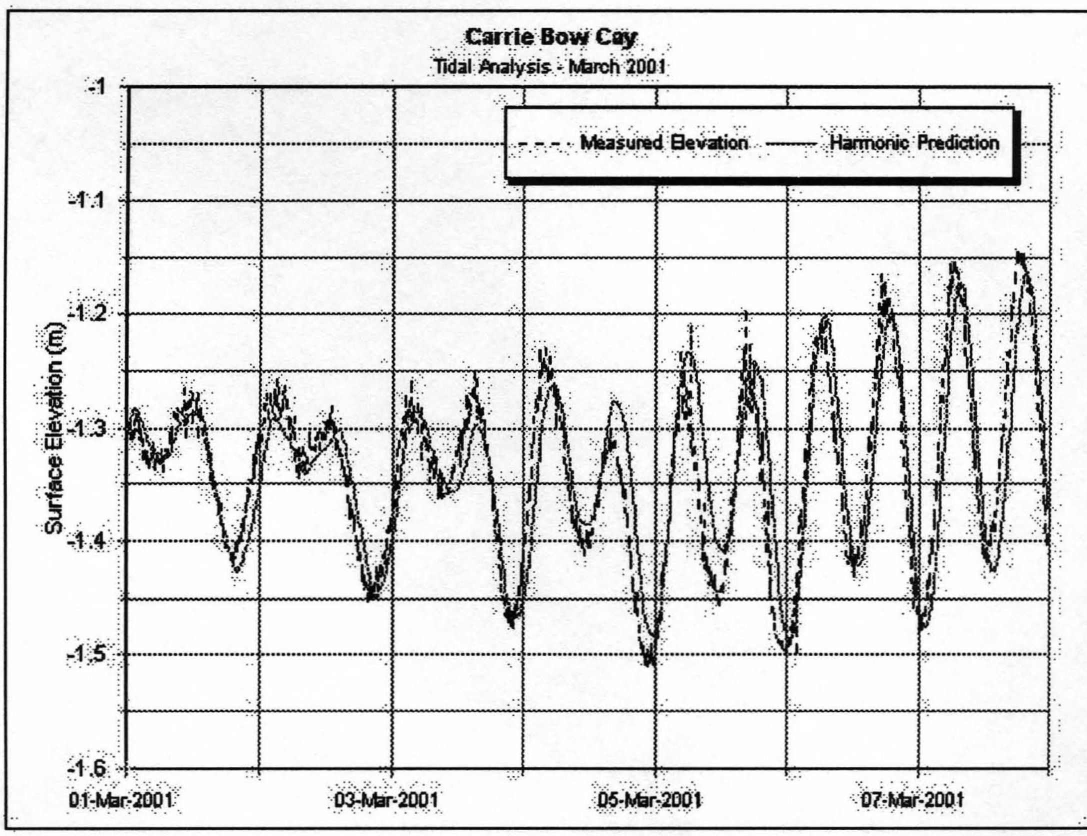

Fig. 16: Comparison of measured and predicted tides at Carrie Bow Cay.

VI. SUMMARY

The need for long-term meteorological and oceanographic measurements to support CCRE projects has been addressed with the real time environmental monitoring system established on Carrie Bow Cay in Belize. Exposed to strong winds, heavy rains, high temperatures, humidity and salty air, electronic equipment is especially susceptible to malfunction and failure. By meeting the design objectives, data is automatically collected, archived and distributed (along with an event activity log) allowing experienced operators to remotely monitor system performance and identify operational status of the system. This ensures that system faults are addressed in a timely manner and, as a result, that quality measurements are maintained. Since data is archived at the field and base stations and on a server at the Smithsonian Institution, it is easily accessed and the potential risk of data loss is substantially decreased.

The use of a self-powered data acquisition and radio communication system at the field site combined with an Internet based data distribution system operating at the base station in Belize and in Washington, DC minimizes operational costs of the system. Taking advantage of the abundant supply of solar energy, the system on Carrie Bow Cay utilizes a solar/battery arrangement to power sensors, data logger and radio. As such, regular operational costs for the sensors and acquisition system are limited to consumable items for in-situ sensors (e.g., o-rings for waterproof connectors, dissolved oxygen sensor solution and membranes, etc.). Additional costs incurred for distribution of data from Carrie Bow Cay to Washington, DC includes minimum monthly telephone and dialup Internet connection charges.

Operating since September 2000 the environmental monitoring system has proven dependable during several major weather events. More importantly, however, the historical sets of continuous environmental data, generated by the system, will assist future research and management efforts of the barrier reef ecosystem. Given the present condition of the ecosystem, still considered pristine despite increasing human activity on the barrier reef, it is imperative to establish a historical baseline and to continue the monitoring activities into the future.

REFERENCES

[1] Rützler, K. and I. Feller, Caribbean Mangrove Swamps, Scientific American, Volume 274, No. 3 pp. 94-99, March 1996.

[2] Rützler, K. and K. Smith, Caribbean Coral Reef Ecosystems 1994/1995 Progress Report, National Museum of Natural History, Smithsonian institution, 1996.

[3] Lang, M.A. and A. Hines, Smithsonian Institution Underwater Research, Marine Technology Society Journal, Volume 34, Number 4, Winter 2000/2001, pp.50-60.

[4] Opishinski, T.B., M.L. Spaulding, and C. Swanson. COASTMAP: An integrated system for environmental monitoring, modeling and management. Presented at the ASCE North American Water and Environmental Congress 1996 (NAWEC 96), Anaheim, CA, June 22-28, 1996.

[5] Spaulding, M. L., S. Sankaranarayanan, L. Erikson, T, Fake, and T. Opishinski, 1998. COASTMAP, An integrated system for monitoring and modeling of coastal waters: Application to Greenwich Bay, Proceedings of the 5th International Conference on Estuarine and Coastal Modeling, American Society of Civil Engineers, Alexandria, VA, October 22-24, 1997.

† This is CCRE contribution no. 618.