FINAL REPORT

AN INVESTIGATION OF THE SOUTH CENTRAL REGIONAL WASTEWATER TREATMENT PLANT OCEAN OUTFALL AND COASTAL ENVIRONMENT

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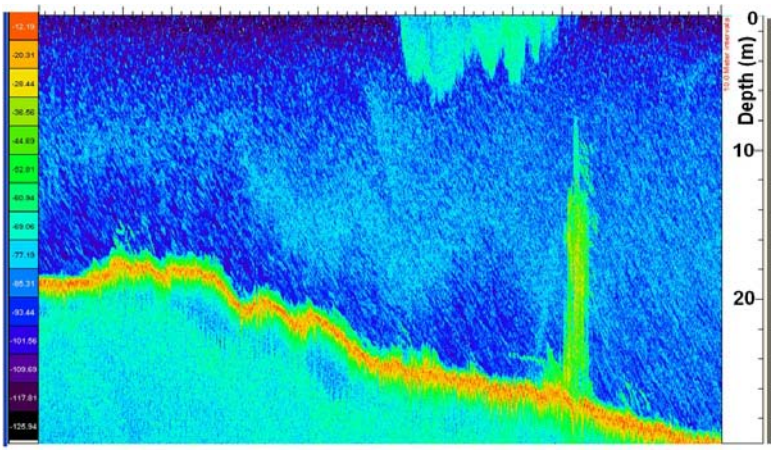

Acoustic backscatter image of the South Central outfall plume

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Final Report

South Central Regional Waste Water Treatment Plant
Florida Area Coastal Environment (FACE) Project

I. Introduction

In 2006, the South Central Regional Waste Water Treatment Plant (SCRWWTP) entered into agreements with the Atlantic Oceanographic and Meteorological Laboratory (AOML) a component of the National Oceanic and Atmospheric Administration (NOAA), to carry out environmental studies on the transport and dispersion of secondarily treated wastewater effluent emanating from the SCRWWTP outfall (denoted "SC" in this document) located in the coastal ocean off southeast Florida. In addition to the studies carried out specifically under said agreements, related studies relevant to the outfall effluent discharges were also carried out as part of the Florida Area Coastal Environment (FACE) program. The agreements were made through the Florida Water Environment Association Utility Council (FWEAUC). FWEAUC and AOML entered into agreements and amendments of said agreements to carry out the studies required. In addition to the studies carried out by AOML, additional studies were carried out by the University of Miami and the Georgia Institute of Technology.

The broad objectives of the studies include: (1) improving the understanding of the oceanic processes affecting the transport and dispersion of discharges into the South Florida coastal environment, (2) gaining data and information on selected nutrient sources and the relative contributions of said sources to the nutrient budget in the coastal ocean, and (3) gaining information on the likely exposure of certain coral reef resources to said sources.

While not an explicitly stated objective, the program provides information of key relevance to Clean Water Act (CWA) considerations. In many cases, because many of the measurements in the present program are not routine or available in the commercial sector, the information gathered is unique. There are several advantages gained by imbedding CWA-relevant measurements within the broader FACE program. These advantages include: (1) the ability to obtain information on effluent plume dispersion in three dimensions, not only for the South Central (SC) outfall effluent plume, but also for other outfall plumes as well, (2) the unique expertise in conducting concurrent sulfur hexafluoride and RD tracer studies (Wanninkhof *et al.,* 2005) in South Florida marine waters, and (3) high quality marine water quality measurements. Thus, CWA questions concerning the outfall discharge effluent plume "impact" on the South Florida coastal environment and coral reefs in particular are supported not only by the South Central outfall studies, but by several other outfall studies, thereby significantly enhancing the credibility of the results obtained. Measurements for nutrients in the ocean are not the same as routine nutrient measurements which can be made by a typical commercial laboratory under standard certified laboratory procedures. Indeed the Ocean Chemistry Division has developed, in agreements with the US EPA, the state of the art methodology to be used in many of the marine water quality measurements to be used in support of the CWA (e.g., see references). The State of Florida has a

specific set of procedures for certified laboratories for the fresh water environment and utilizes EPA methods for the coastal ocean.

Much of the data obtained within the broader study bear directly upon questions of possible impact of the effluent plume on the marine environment and coral reefs proximal to the SC outfall. A key factor in evaluating effluent impact upon coral reefs is the level of exposure of the reefs to the discharged effluent.

To help achieve the above objectives, tracer experiments using both effluent-extrinsic and effluent-intrinsic tracer studies were carried out. In addition, bi-monthly water quality sampling cruises were conducted for a period of one year. Also included, as part of the participation in the larger FACE program to study nutrient sources, was a Boynton Inlet discharge study.

The study area is shown in Figure 1.

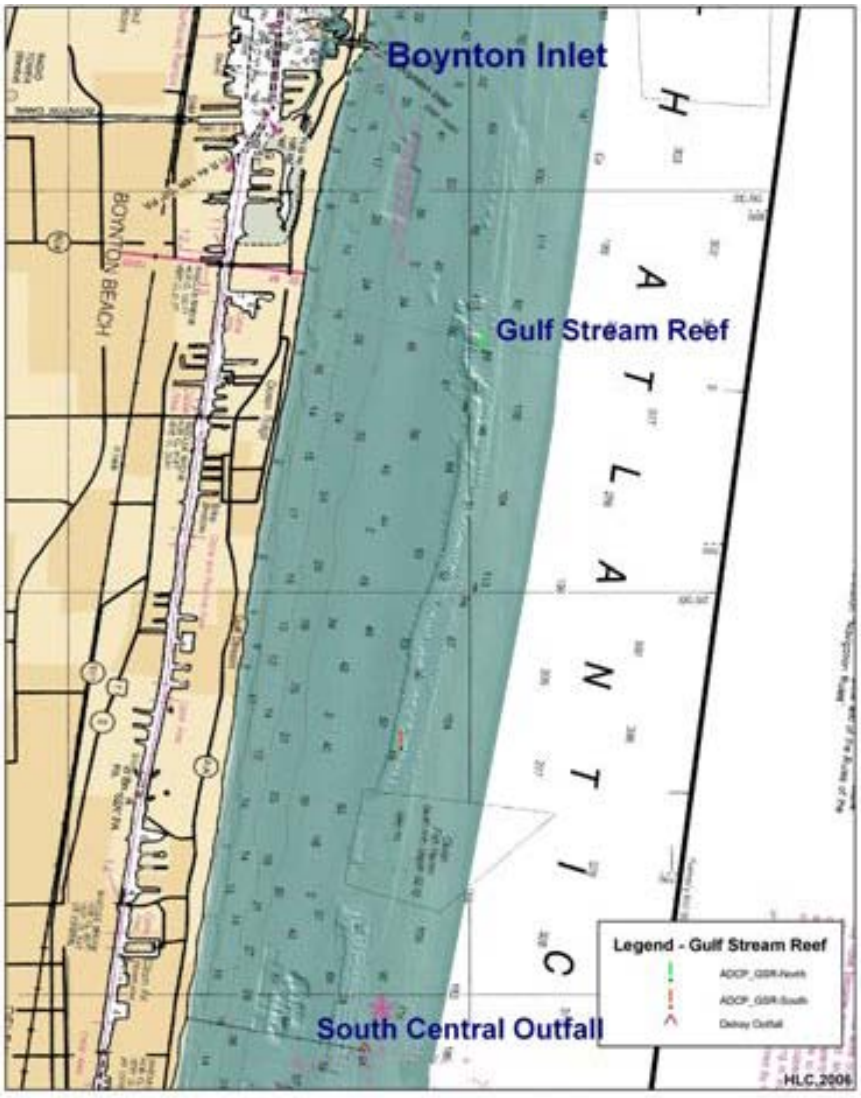


Figure 1. FACE Study Area.

II. Overview of Measurement Approach

A. Ambient Currents

An understanding of plume transport, dispersion and dilution in the coastal ocean rests upon knowledge of the ambient coastal currents. Consequently, instruments to measure ambient currents were installed at the initiation of the present study.

Three In-situ ambient current measurement devices (Acoustic Doppler Current Profilers (ADCP)) were installed in the target area. The first was installed at Gulfstream Reef [GSR] North, a second on GSR south, and a third, GSR Mid, midway between the Boynton Inlet and GSR North. Locations and deployment times are given in Table 1 and shown in Figure 2. These instruments yielded ambient current direction and magnitude measurements through the water column from near the ocean bottom to near the ocean surface. Data from other current meters at other locations were also utilized to help interpret the data obtained from these three instruments. In addition to ambient currents, the in-situ devices also recorded ambient water temperature and pressures. These data are discussed in Section III a.

B. Sampling Cruises

Sampling cruises are the means whereby the chemical and physical parameters of both the receiving ocean waters and discharged SC effluent plume are determined. Sampling cruises can either be undertaken in absence of extrinsic (added) effluent tracers or in conjunction with extrinsic tracers. Extrinsic tracer studiers are described below.

The first major sampling cruise occurred in October 2006. The NOAA R/V Nancy Foster visited each of the major outfalls in the South Florida coastal ocean. Nutrient samples and conductivity-temperature-depth (CTD) casts were obtained at several locations and analyzed for nitrate, nitrite, and ammonium, total suspended solids (TSS), salinity, and temperature. Algal, sediment and water samples were also obtained for isotopic analysis by the University of Miami. The Florida Atlantic University also provided valuable expertise and assistance with measurements. A second cruise on the Nancy Foster was completed in February of 2008. Cruise reports from these cruises will be published in 2009.

In addition to major cruises on the Nancy Foster, a series of six bi-monthly monitoring cruises were undertaken. The dates for the monitoring cruises were (1) June 5-6, 2007, (2) August 29-29, 2007, (3) October 18-19, 2007, (4) February 14 and 19, 2008, (5) May 19-20, 2008, and (6) July 12-13, 2008. These data are discussed in Section III b.

C. Chemical Measurements

There are a number of chemical measurements that are widely used by the scientific community to assess water quality, to determine the sources of water, and to assess the impact of the environment on coastal ecosystems. Nitrogen and phosphorus are essential nutrients required by all organisms, while silicon is an essential nutrient for siliceous organisms such as diatoms.

The form of the nutrient (e.g., dissolved inorganic, dissolved organic, or particulate) is fundamental to their role in the environment. Dissolved nitrogen occurs in natural waters as organic nitrogen, ammonium, nitrite, and nitrate, with nitrate the most stable in oxygenated waters. Dissolved phosphorus occurs in natural water in the forms of organic phosphorus and phosphate. Although organic nitrogen and phosphorus concentrations may exceed that of the inorganic form, they have limited direct bioavailability. The inorganic forms of dissolved nitrogen (nitrate NO_3, nitrite NO_2 and ammonium NH_4) and of phosphorus (phosphate PO_4) are readily available for biological utilization, and typically of greater concern with regard to eutrophication; these are the forms reported in this document. Because nitrate and nitrite may interchange, a commonly reported measurement is the sum of nitrate plus nitrite, denoted N+N.

Elevated nutrients in the coastal ocean are derived from several sources, including treated-wastewater ocean outfalls, atmospheric deposition of particulate and dissolved (e.g., in rain) species, ocean upwelling of deep, cooler waters into the nearshore environment, ground water seepage of water contaminated with septic tanks or other sources, and coastal inlet waters that drain agricultural areas, streets, landfills, and other pollution sources.

Nutrient concentrations can be reported in different units of measure. The two principle units of measure are micro-Moles per liter (µM) and milligrams per liter (mg/L). They can be readily interconverted:

C[µM]*X[g/mole]/1000 = C[mg/L]

C[mg/L]*1000/X[g/mole]=C[µM]

Where X is the atomic weight of nitrogen (14 g/mol), phosphorous (30.974 g/mol) or silicon (28.068 g/mol). Concentrations in µM units in this document were computed that way (in the literature, one may find the µM calculation using a different form, e.g., NO2 instead of N).

D. Extrinsic Tracer Studies

The first of two planned tracer studies was conducted in February 2007. This study was denoted the Florida Outfalls and Coastal Inlet Experiment (FOCITE). In this study Rhodamine-WT dye (RD) (see YSI 2001) and sulfur hexafluoride (SF_6) gas were introduced into an outgoing tidal flow in the Boynton Inlet on 22-February-2007 and into the SCRWWTP outfall effluent flow for a 48 hour period commencing on 26-February-2007. The RD and SF6 were then tracked by ship using a sensor-rich towbody for a number of days. The towbody was equipped with a hose and a pumping system to obtain water samples. In addition, two fluorometric sensors were implanted at the bottom and at mid-water above a location on the GSR. These data are discussed in Section III c.

The second extrinsic tracer study (FOCITE-2) was carried out in July 2008. Data from this cruise will be published as a NOAA Technical Report in 2009.

III. Data Obtained

A. Ambient Current Data

Three ADCP units (RD Instruments, Poway CA, "workhorse" model) were employed at or near the GSR, denoted GSR-north, GSR-south, and GSR-mid ADCPs. Deployment information is given in Table 1 and locations are shown in Figure 2 (there were breaks in the data set due to instrument maintenance requirements). Data from these units is of considerable value in understanding the wide variety of data in this study. Because the data from the GSR-north covers the greatest time, we will present those data in this report.

Table 1. Gulfstream Reef ADCP Deployments

Site Name	Latitude	Longitude	D (m)	Frequency	Start Date	End Date
GSR-Mid	26°32.004N	80°2.146'W	14.8	300 kHz	2/20/2007	4/13/2007
GSR-North	26°31.247'N	80°1.939'W	14.5	600 kHz	4/4/2006	9/8/2007
GSR-South	26°29.272'N	80° 2.350'W	16.4	1200 kHz	9/29/2006	7/18/2008

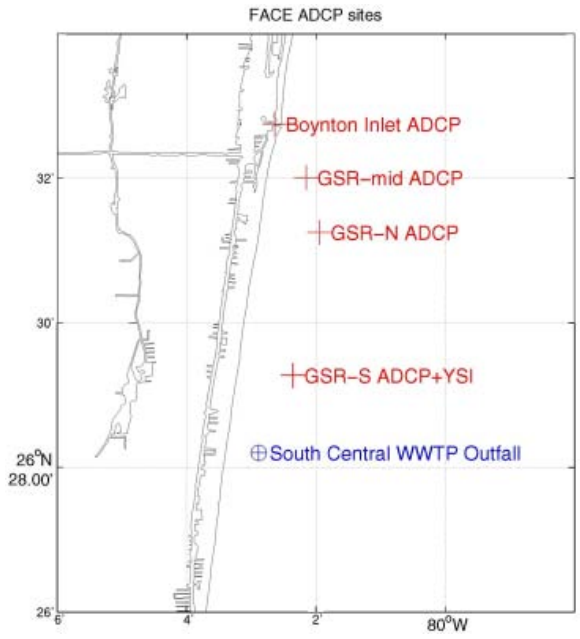


Figure 2. Deployment locations for underwater instrumentation utilized in the this report. The Boynton Inlet ADCP is different from the other ADCP units in that it employs a horizontal (side-looking) beam that measures the flow across the Inlet. The other ADCP units employ a vertical beam for ocean current profile measurements in the U (east-west), V (north-south), and W (up-down) directions.

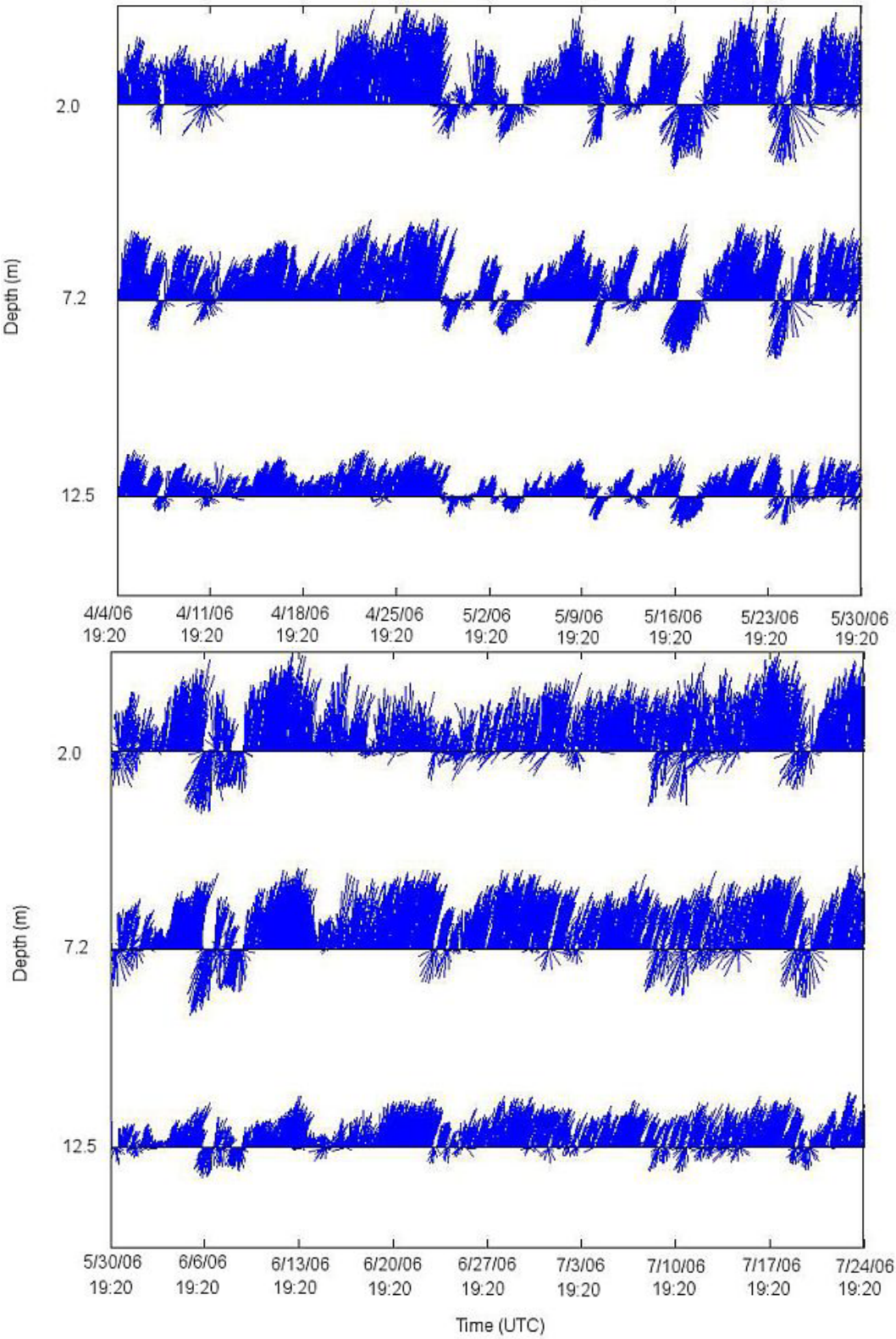


Figure 3. Stick-figure presentation of the ambient ocean currents at three depths for 4-April-2006 through 30-May-2006 (upper panel) and for 31-May-2006 through 24-July-2006 (lower panel). Recorded by the GSR-north ADCP. The sticks point to direction of current flow; length is proportional to current velocity.

Shown in Figure 3 is the ambient current field from GSR-north for the time period 4-April-2006 through 30-May-2006, at three depths (2.0 m, 7.2 m, and 12.5 m). It can be seen from these figures that the current direction is generally northward, essentially uniform with depth, and the largest current magnitudes occur in the upper part of the water column. It is also notable that the episodes of southward current are brief, rapid, and often have current speeds comparable to the northward current speeds. What are the sources of these rapid current changes? A possible explanation is wind. We examined the wind data from the nearby NOAA data buoy LKWF1 (26°36'42"N, 80°2'0"W, http://www.ndbc.noaa.gov/station_page.php?station=LKWF1) for the period of 1-13 June 2006, where a notable southerly pulse occurred; there was evidence to support wind as the causative agent.

A more likely cause is oceanic not atmospheric. It is well known that meanders or eddies in the Gulf Stream can perturb the central coastline of eastern Florida (e.g., Smith 1983; Fiechter and Mooers 2003). The pattern of current direction seen in Figure 3, i.e. north-east-south-west, would be observed in the passing of an eddy. The impact of Gulf Stream eddies on the coastal waters of southeast Florida is currently under study.

We wish to examine the current data from GSR-north in more detail with a more complete data set. In Figure 4a, ambient current distributions and cumulative histograms for GSR-north from 4/4/2006 to 9/8/2007 are presented. In Figure 4a left panel, the distribution of the V-component of current for the 3.5 meter depth is shown. Note that both northern and southern currents are observed, but that the mean current is about 35 cm/s (0.7 kt) to the north. In Figure 4a (right panel), the cumulative distribution of the v component of ambient current corresponding to Figure 4a left panel is shown; the ambient current is directed to the north approximately 86% of the time. Figures 4a (middle panel) corresponds to the above but for the 8.0 meter depth; again, the current is northward about 86% of the time. Figure 4a (bottom panel) continues the pattern, but for 12.5 m depth (the bottommost bin of data from the instrument that is acceptable); again, the current is northward 86% of the tie. We also see the current distributions becoming narrower and the velocity becoming lower (because of drag from the sea floor) as the depth increases.

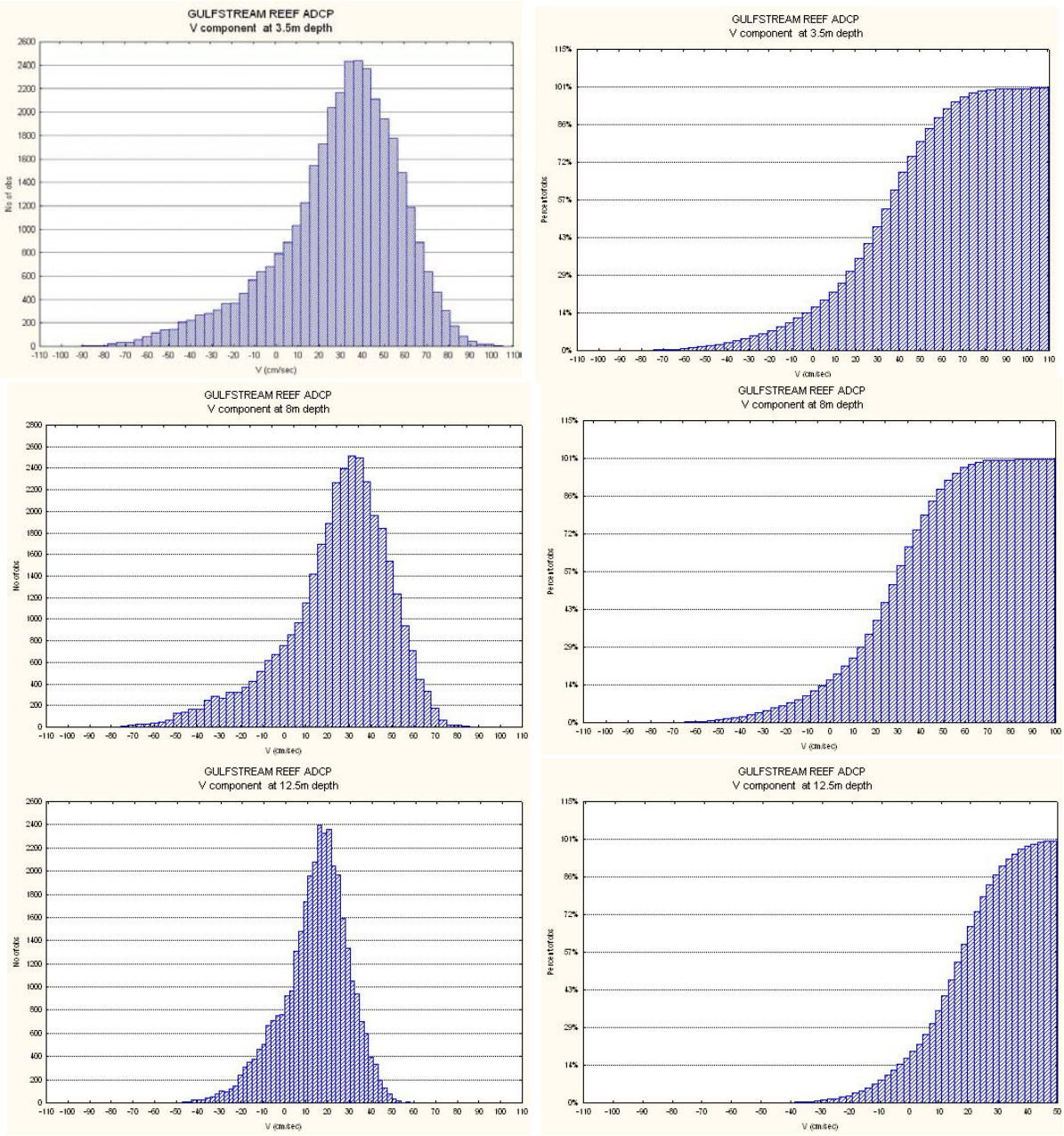


Figure 4a. Upper left: the distribution of the v-component (north-south) current magnitude for the 3.5 meter depth for the time period 4-April-2006 through 8-Sept-2007; upper right: The cumulative distribution of the v component of the same data set. Middle and Bottom panels: similar presentations for the 8 meter and 12.5-meter depth. Recorded by the GSR-north ADCP.

The mean V current and V current extremes for various depths are shown in Figure 4b (upper panel), and the mean U current and U current extremes are shown in Figure 4b (middle panel). Note that both the mean current and current extremes decrease as a function of depth for both the V and U current components.

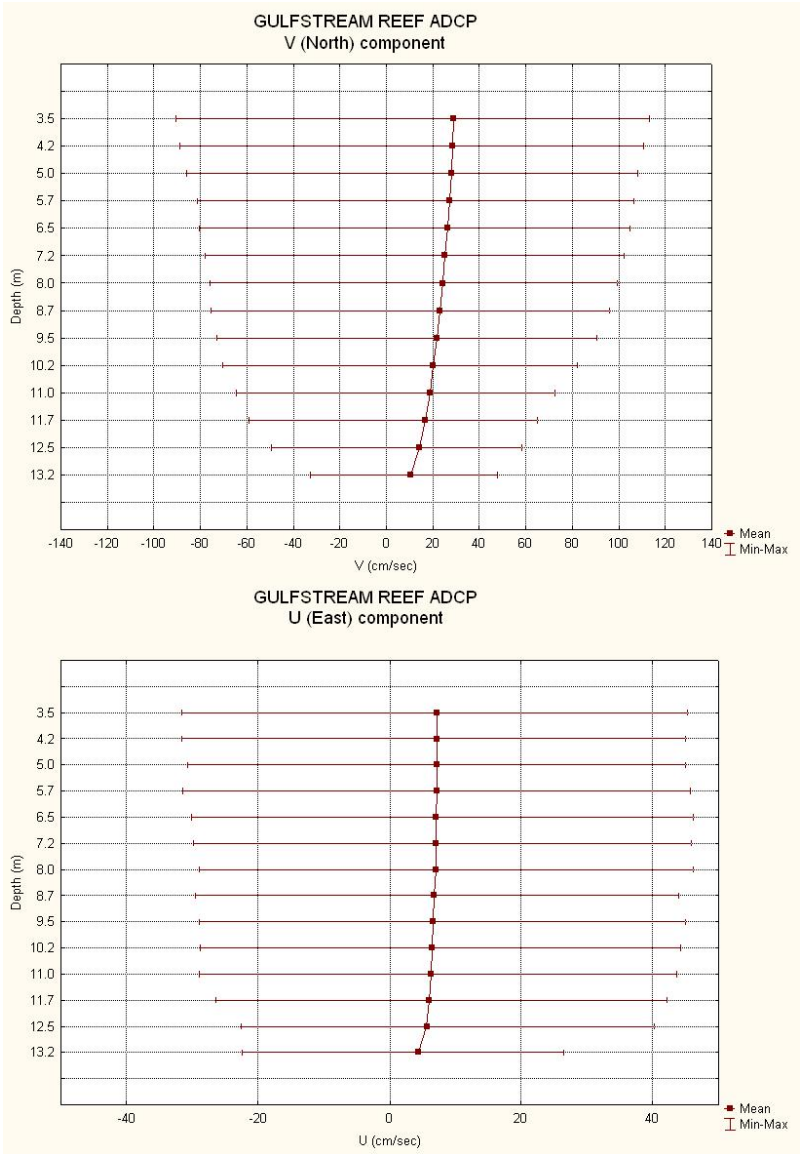


Figure 4b. Current averages and extremes at various depths. Upper panel: U (east-west) current. Middle panel: V (north-south) current. Bottom panel: W (vertical) current. Recorded by the GSR-north ADCP from 4-April-2006 through 8-Sept-2007.

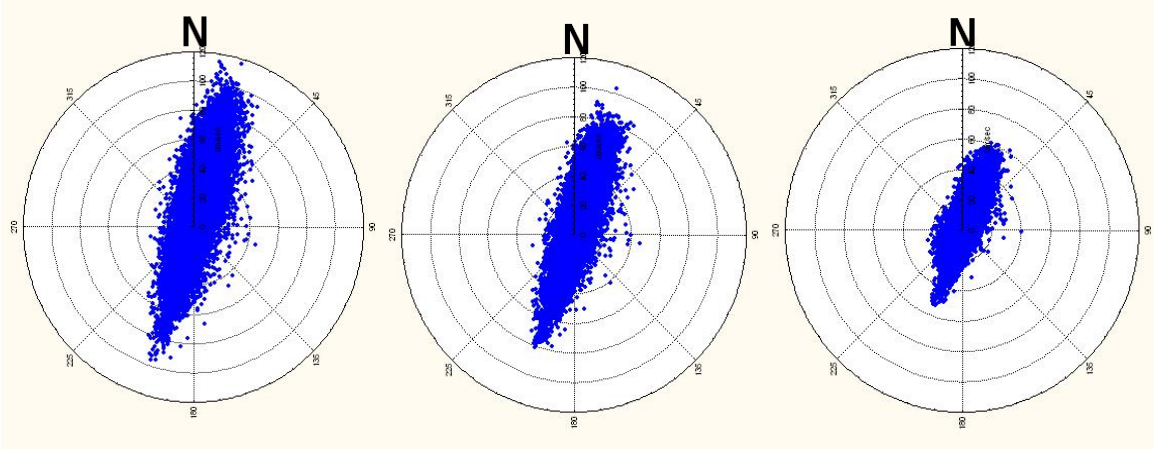


Figure 4c. Polar current plots for 3.5 meters depth (top panel), 8.0 meters depth (middle panel), and 12.5 meters depth (bottom panel), over the same time period as in Figure 4a and 4b, from the GSR-north ADCP.

The polar current plots for the GSR-north data set are shown in Figure 4c. This presentation indicates consistent eastward tilt of the mean current, at approximately the same angle as the vicinal coastline. Here also is seen the lower mean velocities with increasing depth.

B. Water Quality Sampling Data

i. Nancy Foster Cruise, October 2006

This cruise was designed to obtain data from each of the six treated-wastewater outfall plumes in Southeast Florida. The cruise track for the R/V Nancy Foster is shown in Figure 5. The sampling locations and cast locations are shown in Figure 6. Samples were obtained at each of the outfalls as well as sites removed from the immediate boil areas. Results of sample analyses are given the Appendix. An image of the SC plume derived from acoustic backscatter data is shown in Figure 7. Note the surface expression of the plume. Three deepwater casts (BRI, PCI, and MCI) were made at the locations shown in Figure 7. The results from these casts are shown in Figure 8, are the temperature and nutrient concentrations versus depth at five different depths. As expected, the nutrient values are very low in the upper part of the water column but increase significantly with depth; this deeper water can be advected near shore by coastal oceanographic processes (Fiechter and Mooers 2003; Smith 1983).

Measurements of nitrate and nitrite were made for each of the effluent boils (results from the SC boil were lost due to instrument failure). The sum of nitrate plus nitrite (N+N) is a useful and widely used measurement and will be employed in this report. Generally, the boil, which is the surface expression of the upward buoyant treated-wastewater plume, is a region of rapid mixing with substantial variation of constituent concentrations over small spatial scales, e.g. one meter. Each of the outfall boils was sampled. An important number is the average of the boil N+N concentrations. For the boils sampled in October 2006, this number is 0.10 milligrams per liter (mg/l) or 7.2 µM. To place this number in context

of the surrounding water environment in South Florida, Figure 9 lists N+N values measured at relevant locations in south Florida coastal waters.

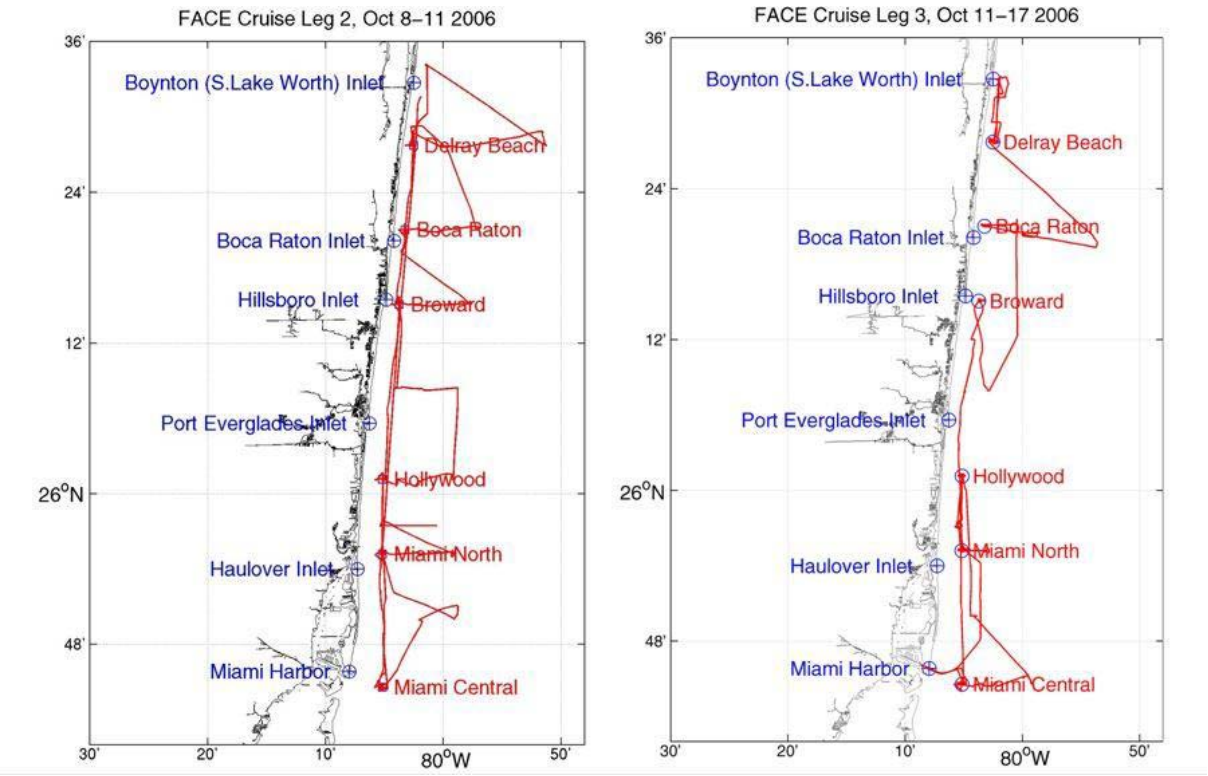


Figure 5. Cruise track for the R/V Nancy Foster 2006 Cruise..

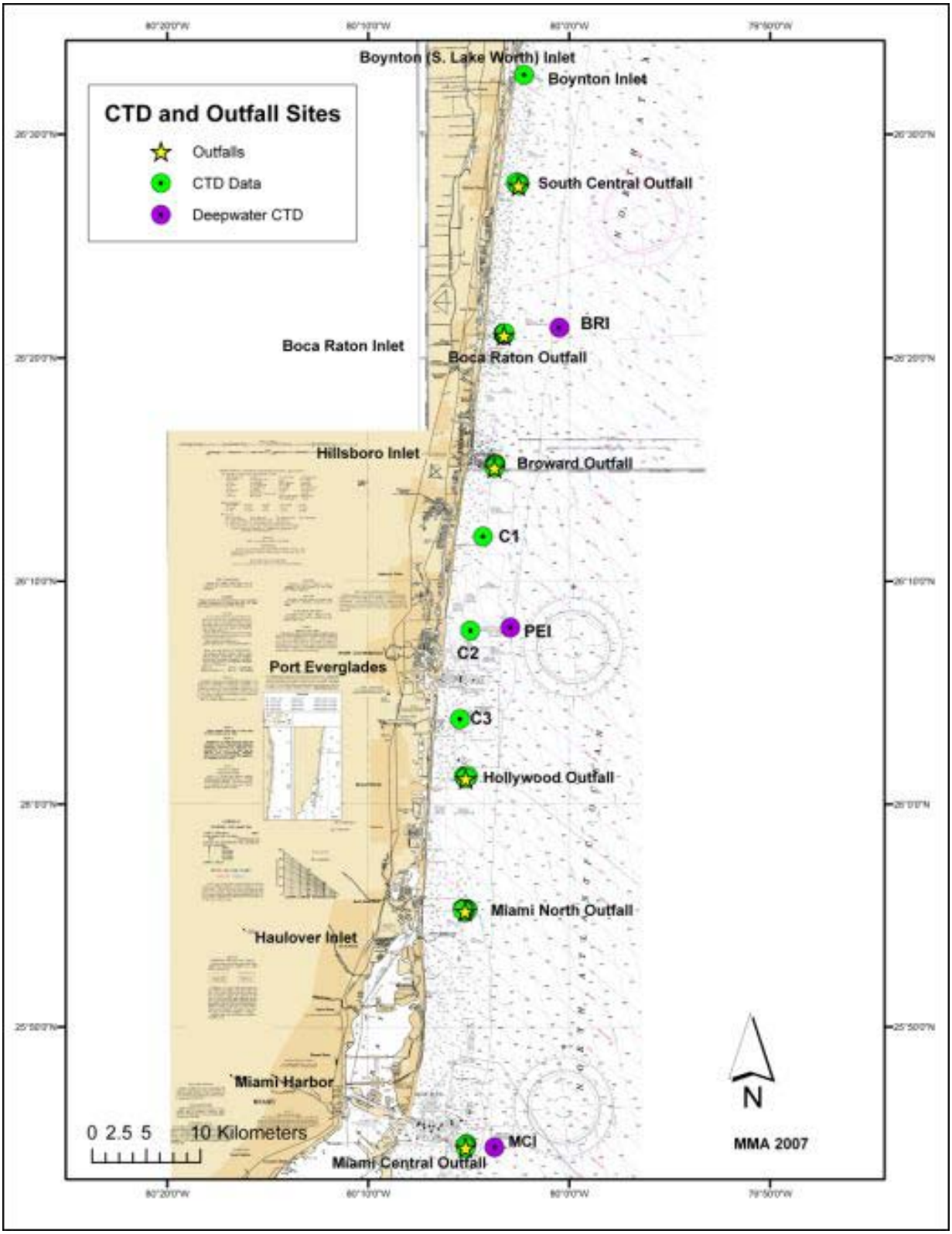


Figure 6. Nancy Foster 2006 cruise sampling locations and cast locations.

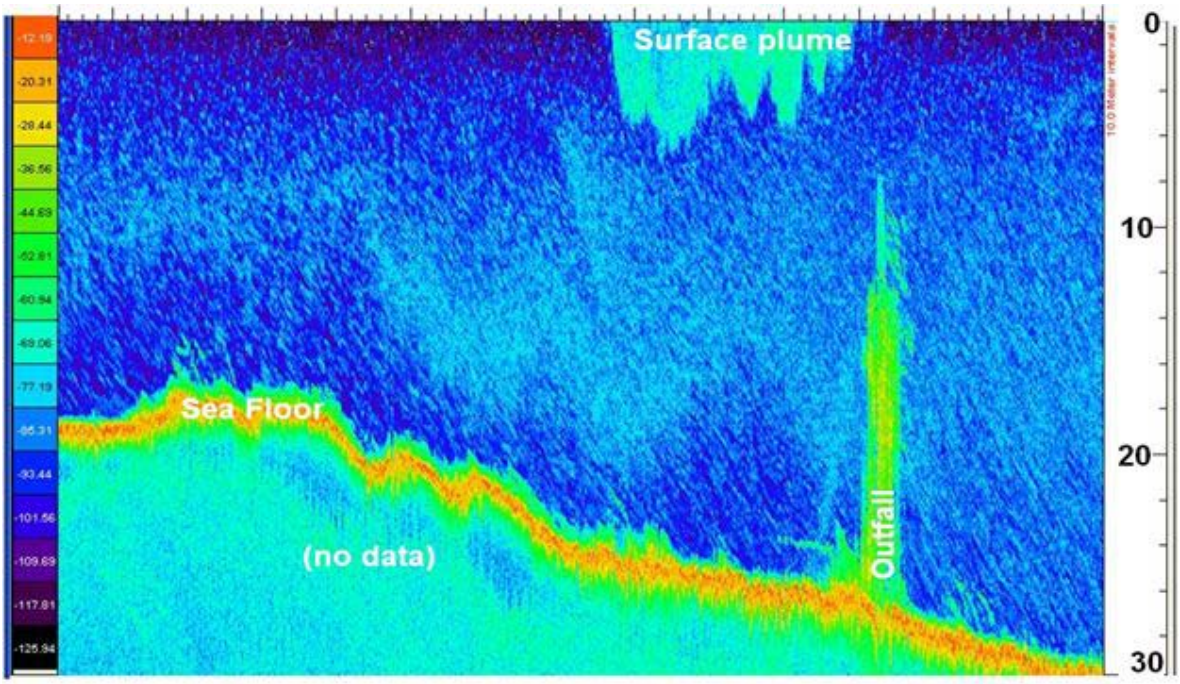


Figure7. Acoustic backscatter image of the SC Outfall plume.

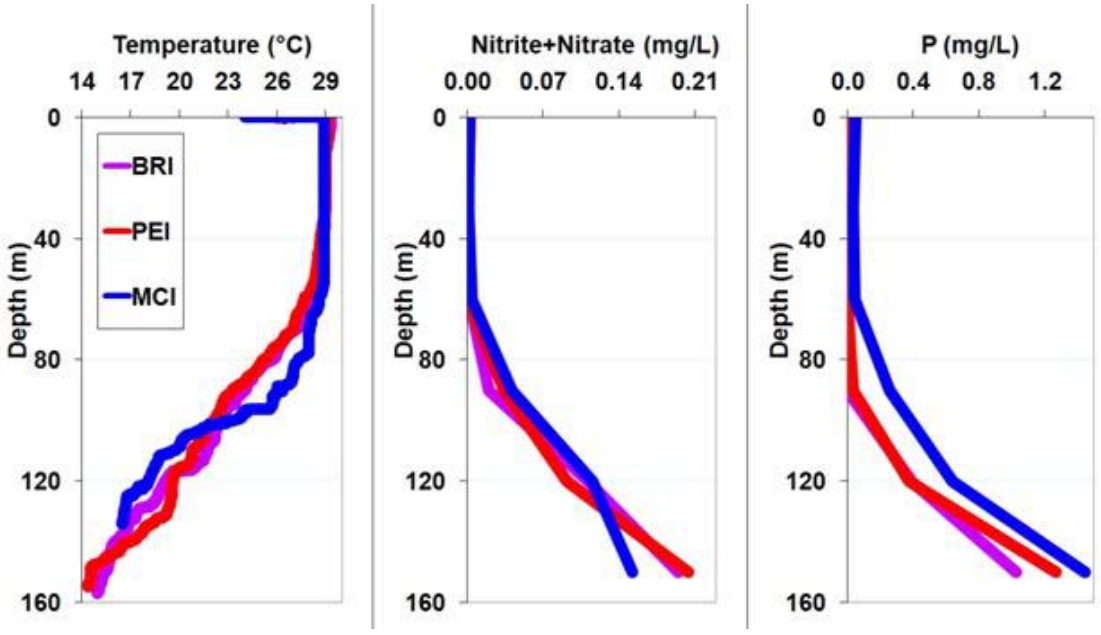


Figure 8. Depth profiles of temperature and nutrient values obtained at 5 different depths from the 3 deep water casts shown in Figure 6 (2006 Nancy Foster cruise).

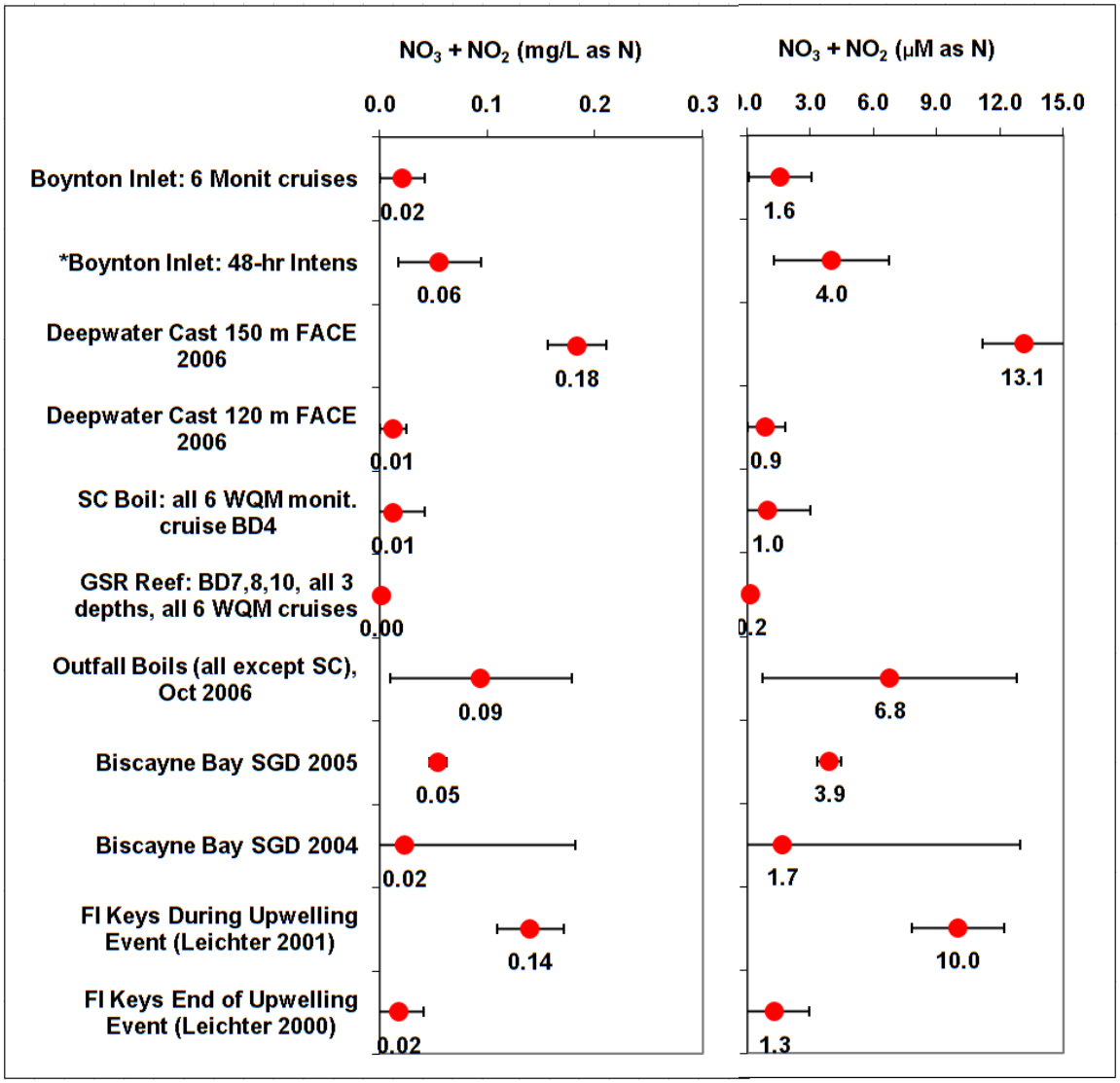


Figure 9. List of N+N values measured at relevant locations off of south Florida, shown in both µM and mg/L units. Red circle is the average; horizontal bar is the standard deviation. *The highest concentration of N+N from the Boynton inlet 48-hr intensive studies were 4.4 µM (June 2007) and 10.3 µM (September 2007).

ii. Bi-Monthly Water Quality Sampling

Six bi-monthly water quality sampling cruises have been carried out in and around the Boynton-Delray (BD) coastal waters. Eighteen sampling sites (BD1-BD18) were chosen, these are shown in Figure 10. Table 1 gives the coordinates, distance from outfall, distance from Boynton Inlet, and depth for the sites. Table 3 gives the dates of the cruises and the approximate ocean current direction during the cruises. A full description of the water quality monitoring program is given in the "Boynton-Delray Coastal Water Quality Monitoring Plan", NOAA internal document, July 2007 (see reference list).

The eighteen sampling locations were selected to address several questions concerning the SC outfall discharge. These questions include: 1) What is the change in concentration with distance from the outfall for quantities of interest (e.g., nutrients)? 2) Is there a decreasing gradient of concentration present with distance north or south of the outfall? 3) What is the effect on the SC effluent plume from the nearby (~9 km north) Boynton Inlet plume? 5) Are there seasonal changes in the concentrations? 6) Can we define 'background' concentrations for nutrients in this area, and are there seasonal or other regular changes in these background concentrations?

Consequently, the selected sites included locations north and south of the outfall at various distances, a site at the boil, sites along the GSR, a site inland from the GSR to investigate nutrient input from coastal run-off or ground water discharge, sites within, north, and south of the Boynton Inlet, and sites within the Lake Worth Lagoon (see Table 1). These categories of sampling sites can be used to efficiently report the overall results, which we do in Figure 11 and Table 4. Clearly, the Lagoon (Lake Worth) and the Inlet have excessively high concentrations of the four nutrients. Some increases of concentrations are found at the boil; however, the concentrations decrease rapidly away from the boil.

These data are broken down by month and by water depth in the subsequent Figures (12a – 12d), for all six monitoring cruises. Each graph shows site numbers on the horizontal axis and nutrient concentration in micromoles on the vertical axis. A number of important results are evident. In general, the concentrations of nutrients from the Lake Worth and Boynton Inlet sites (BD13, BD16, BD17, and BD18) far exceed that of other sites during northward ocean flow. The August 2007 cruise was notable in that most of the samples were obtained during southerly flow; it is likely that the site locations south of the Inlet (BD11, BD12) were not located sufficiently inside the Inlet plume during southerly flow because the concentrations from those sites are not high. The lowest concentrations are seen at the GSR and Inner sites (BD6-BD10). The boil is dynamic and not always easy to find; If the boil and/or plume maximum was sampled (e.g., August 2007), concentrations of P, N+N, and NH4 are elevated (but not Si), and decrease rapidly to the south. During northerly flow, any elevated nutrient concentrations at the outfall (BD4) decrease rapidly to the north, with concentrations reduced to GSR/Inner levels usually by BD7 (2.9 km north of the outfall). In Figure 12a, the highest N+N measurements values recorded for June and August 2007 occur at station BD 17 and BD 4 with values of 25 µM and 8 µM respectively. Station BD 17 lies within the Lake Worth Lagoon and station BD 4 is the SC outfall terminus. The highest values are measured in the upper water column (near-surface) and indicated by the green columns. Of particular interest are the N+N values in the area of the GSR. The stations in the area of the GSR are BD7, BD8 and BD10. For June of 2007, N+N concentrations were 0.12 µM, 0.12 µM, and 0.36 µM (resp.). For August of 2007 the corresponding values measured were as follows: 0.28 µM, not detected, 0.02 µM. As can be seen from Figure 12a, these values over the reef are among the lowest N+N values measured. Station BD9 is between the reef and shore; concentrations from this site are similar to that of the GSR sites.

Table 2. Boynton-Delray sampling sites: locations, distances from outfall and inlet, and depths.

Station #	Latitude	Longitude	Dist to outfall (km)	Dist to Inlet (km)	Depth (m)
BD-1	26.42565	-80.04542	4.05	13.32	35
BD-2	26.44212	-80.04725	2.26	11.49	6
BD-3	26.45803	-80.04252	0.43	9.72	33
BD-4	26.46192	-80.04208	0.00	9.29	32
BD-5	26.46628	-80.04182	0.49	8.80	30
BD-6	26.47558	-80.03995	1.53	7.77	30
BD-7	26.48773	-80.03933	2.88	6.43	20
BD-8	26.51073	-80.03543	5.47	3.93	20
BD-9	26.50833	-80.04167	5.16	4.13	15
BD-10	26.52273	-80.03228	6.83	2.74	16
BD-11	26.53333	-80.03583	7.96	1.52	13
BD-12	26.53874	-80.0398	8.55	0.81	8
BD-13	26.54542	-80.043	9.29	0.00	5
BD-14	26.54747	-80.04003	9.51	0.37	3
BD-15	26.55907	-80.03327	10.83	1.80	13
BD-16	26.54626	-80.04818	9.40	0.52	2
BD-17	26.54266	-80.04793	9.00	0.58	2
BD-18	26.53944	-80.04954	8.65	0.93	2

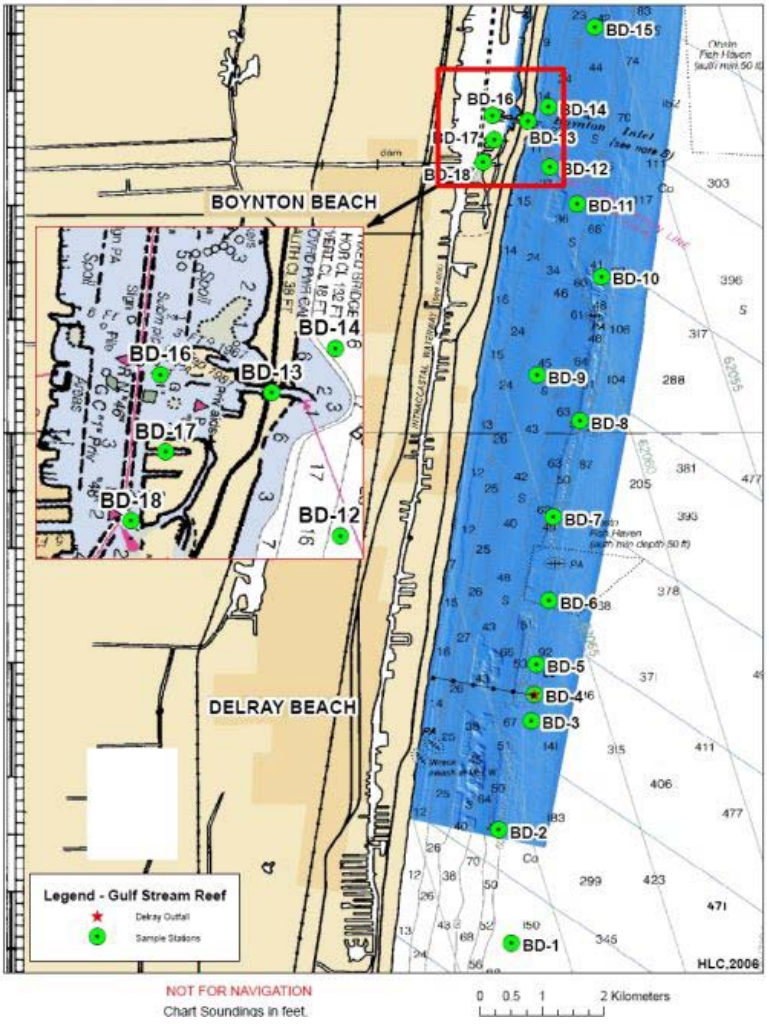


Figure 10. Sites selected for the water quality monitoring program.

In addition to N+N, other parameters include ammonia, silica and phosphate were measured. Shown in Figure 12b are the ammonia values measured for June and August 2007 and May 2008 for sites BD 1 through BD 10. A peak value of 22.50 µM (0.315 mg/L) for ammonia was recorded in the boil in August of 2007. The boil was apparently missed in June of 2007, when a maximum value of 0.59 µM (0.008 mg/L) was recorded. However, the value observed is consistent with high-frequency towed ammonia system measurements (see Section III c) made in February 2007. Note also that elevated ammonia levels are seen in samples in the environs of the Boynton Inlet.

Phosphate values measured in June, August, and October 2007 and February 2008 are also shown in Figure 12c. The highest phosphate values are seen in the vicinity of the inlet and to a lesser degree in the vicinity of the outfall. Silica values measured in June, August, and October 2007 and February 2008 are also shown in Figure 12d. Highest silica values are measured in the environs of the Boynton inlet.

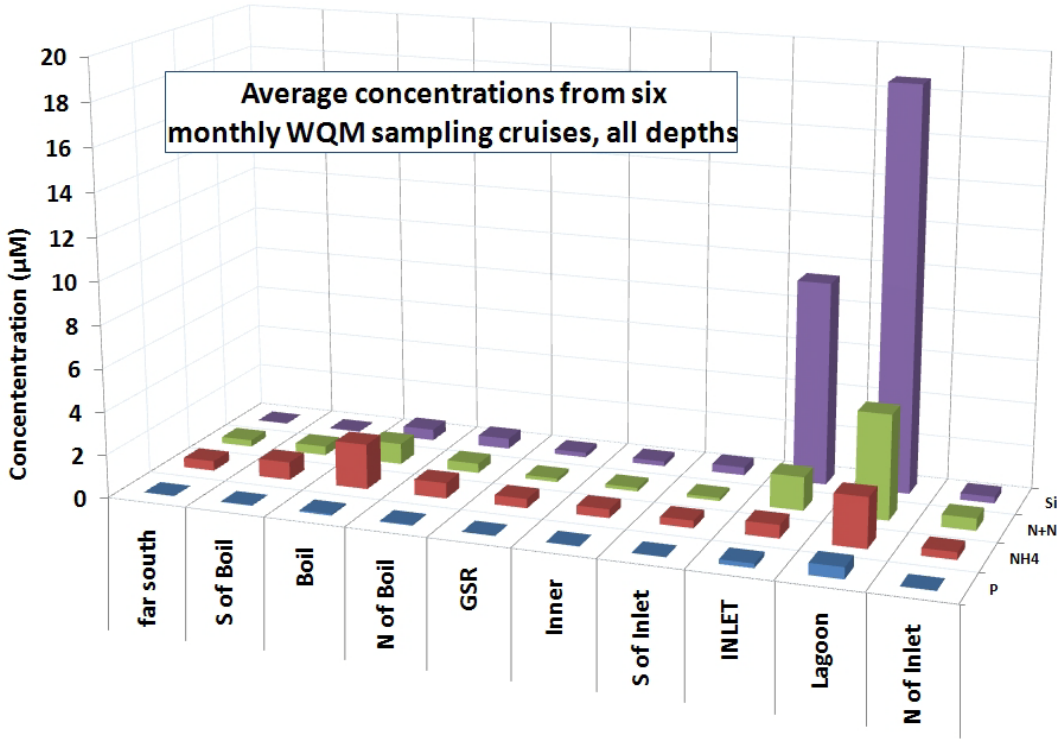


Figure 11. Concentration averages for groupings of sampling site data for nutrients. Referring to Table 2, Far South = BD1 and BD2; S of Boil = BD3, Boil = BD4, N of Boil = BD5, GSR = BD6, 7 ,8, and 10, Inner = BD9, S of Inlet = BD11 and BD12; Inlet = BD13, Lagoon = BD16, BD17, and BD18, and N of Inlet = BD14 and BD15.

Table 3. Approximate Ocean Currents during times of study

Study	Start Time	End Time	Approx. Dir. Of Ocean Current
June 2007	6/5/2007 10:17	6/6/2007 13:53	North~100%
August 2007	8/28/2007 9:15	8/29/2007 9:50	South ~79%
October 2007	10/18/2007 8:10	10/19/2007 10:00	North~100%
February 2007	2/14/2008	2/18/2008	North~75% South~25%
May 2008	5/19/2008 8:30	5/20/2008 14:50	North~100%
June 2008	6/12/2008	6/13/2008	Current reversal (N to S)

Table 4. Concentrations (µM) of nutrients in selected portions of the sample sites.

	#1,2	#3	#4	#5	#6-7-8-10	#9	#11,12	#13	#16,17,18	#14,15
	far south	S of Boil	Boil	N of Boil	GSR	Inner	S of Inlet	Inlet	Lagoon	N of Inlet
P	0.01	0.02	0.07	0.04	0.01	0.01	0.01	0.21	0.54	0.01
NH4	0.45	0.83	2.11	0.72	0.43	0.41	0.35	0.62	2.34	0.35
N+N	0.31	0.42	0.97	0.44	0.17	0.17	0.14	1.56	4.86	0.56
Si	0.01	0.03	0.52	0.49	0.22	0.22	0.37	9.43	18.70	0.30

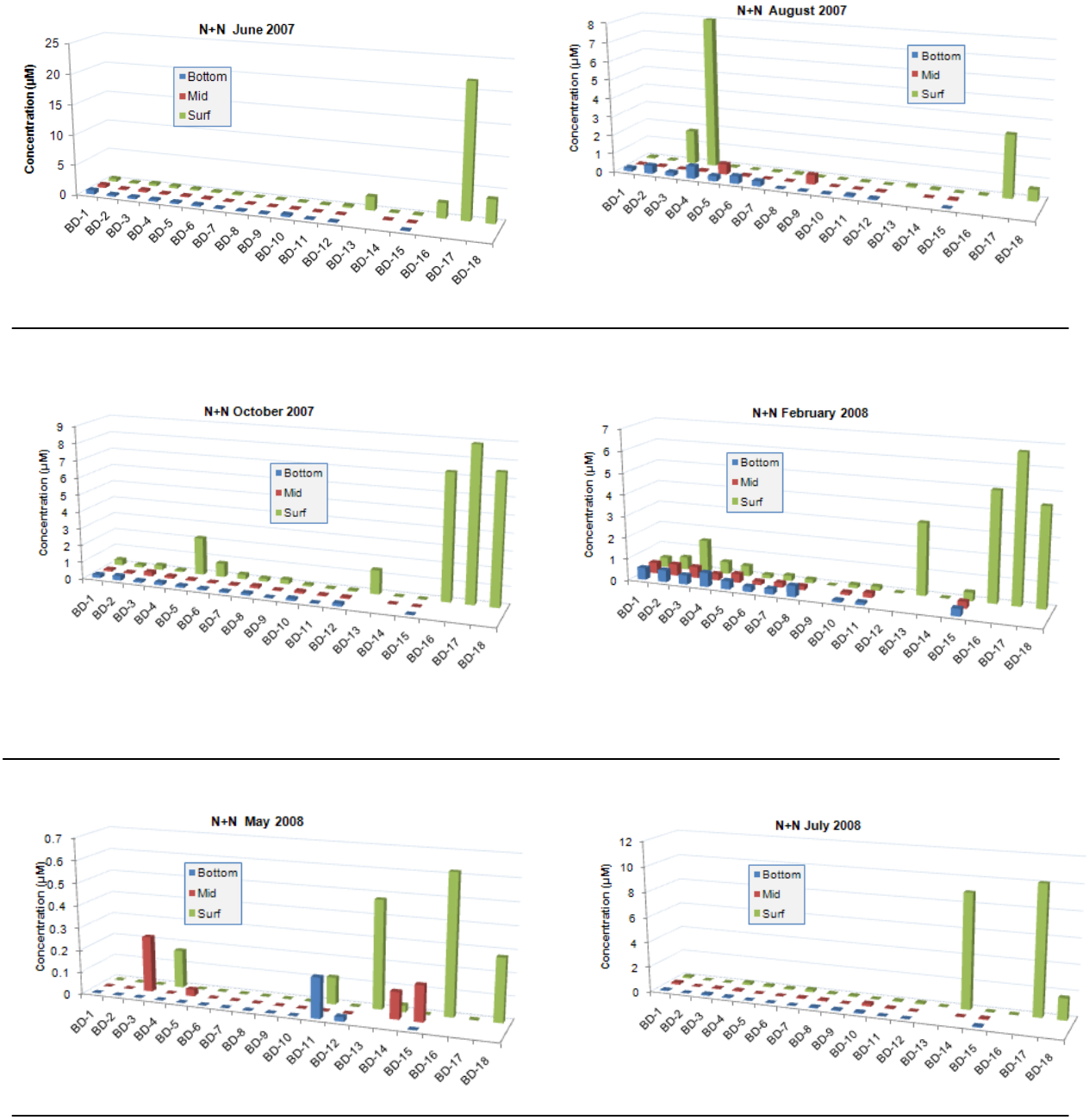
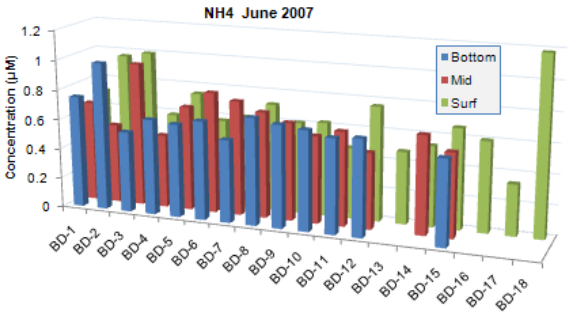
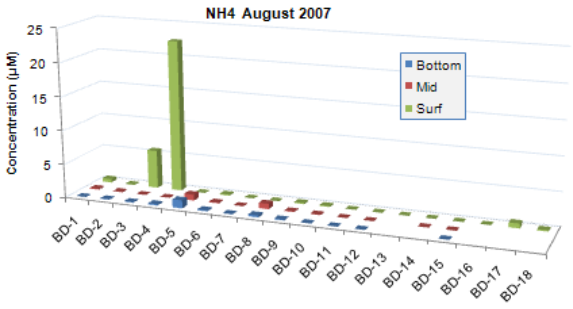
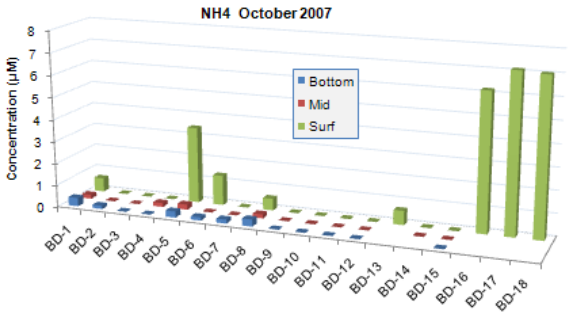
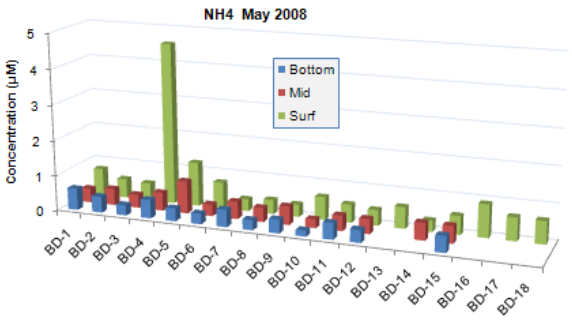


Figure 12a. Measurements obtained for Nitrate and Nitrite (N+N) for the June 2007 (upper left), August 2007 (upper right), October 2007 (middle left), February 2008 (middle right), March 2008 (lower left), and July 2008 (lower right), at three depths. Shallow locations had fewer sampling depths. Sample designations as in Table 2.









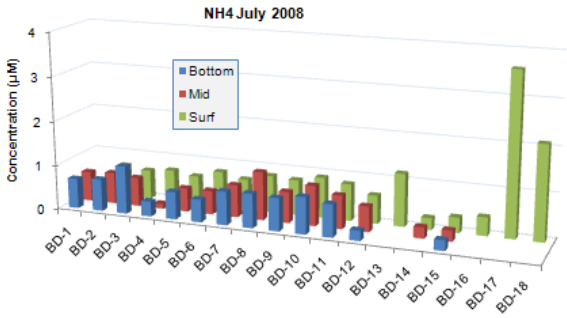


Figure 12b. Measurements obtained for ammonium (NH_4). No measurements were made in February 2008. Presentation details similar to Figure 12a.

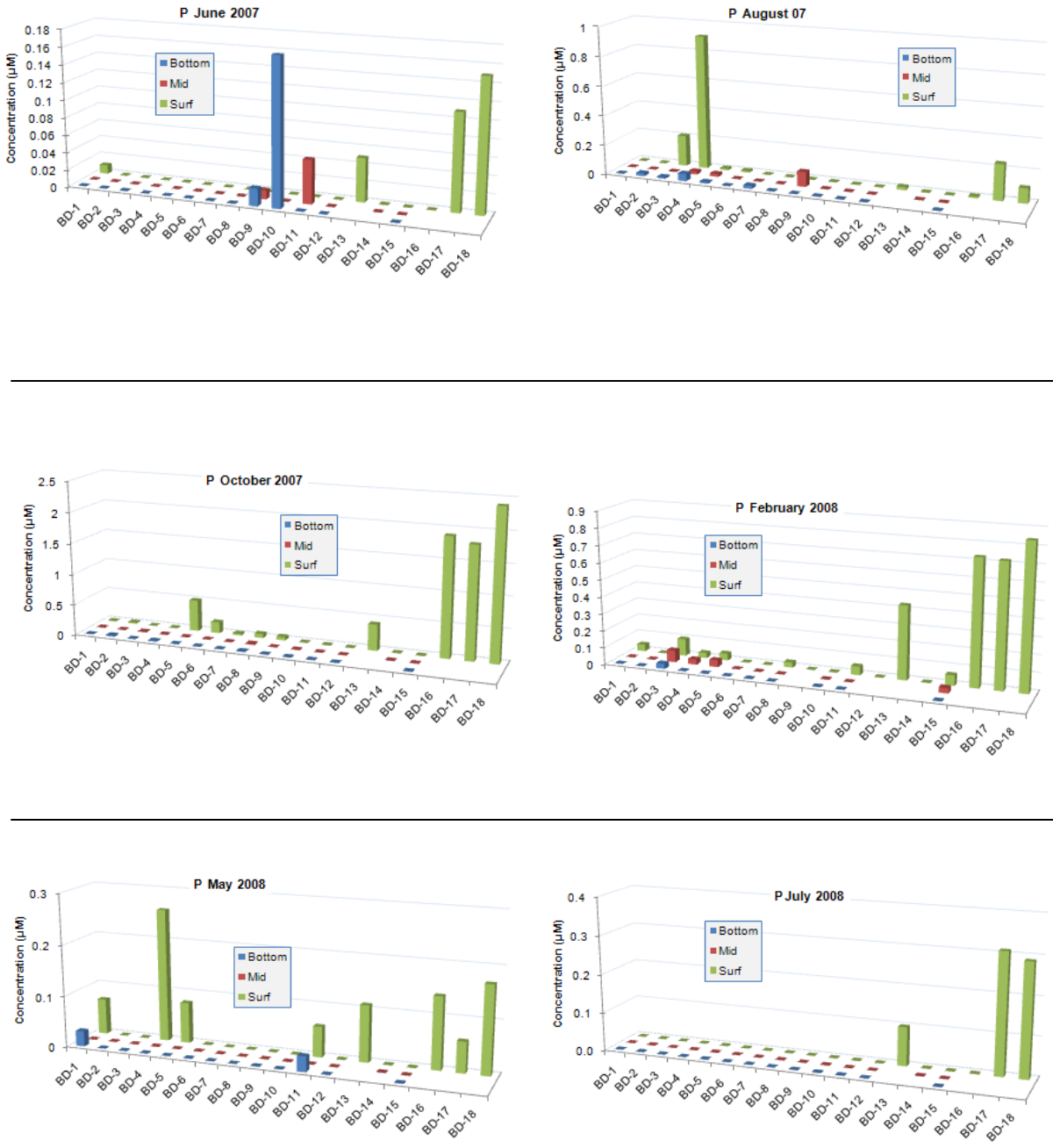


Figure 12c. Measurements obtained for phosphate. Presentation details similar to Figure 12a.

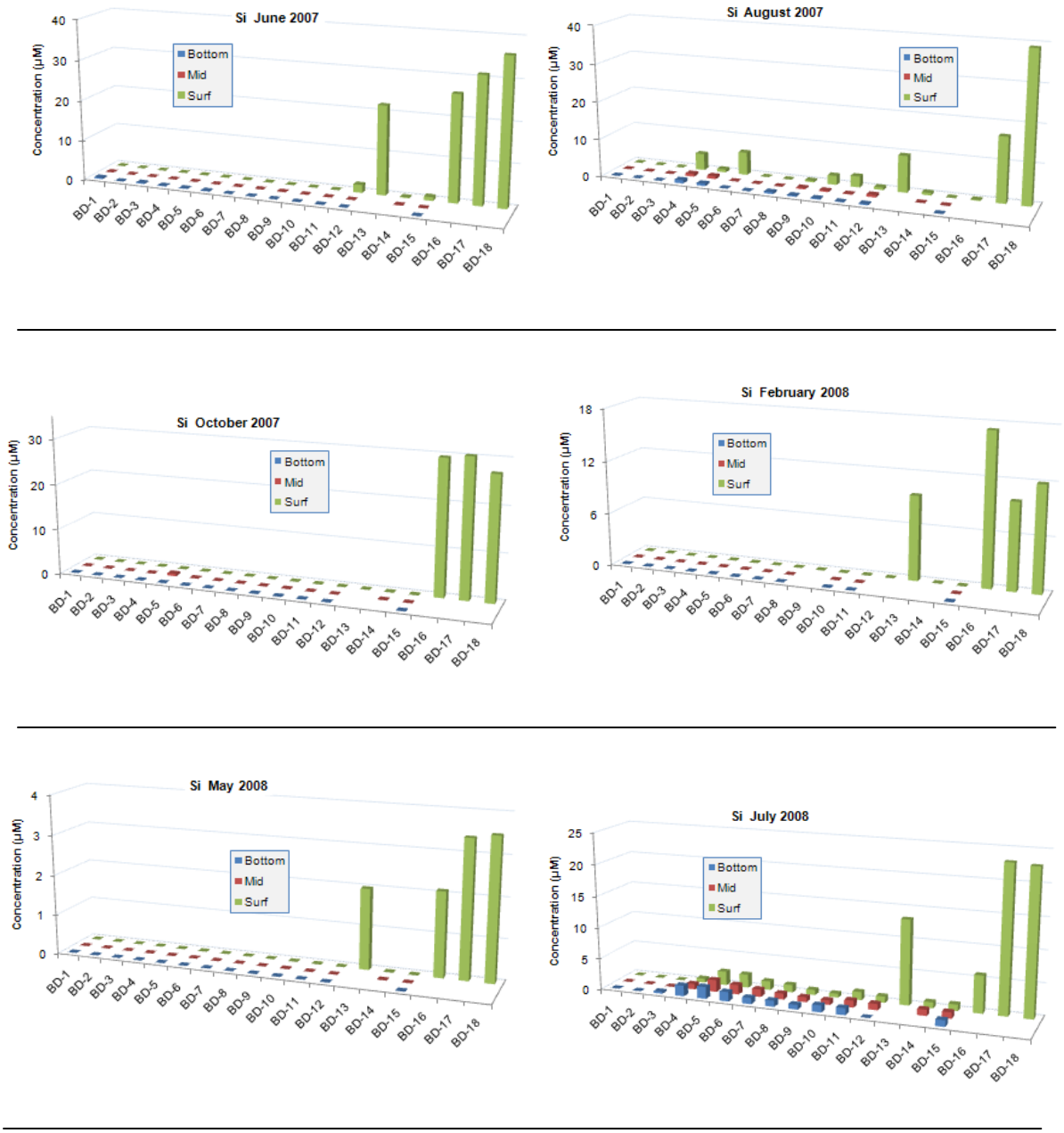


Figure 12d. Measurements obtained for silica. Presentation is the same as in Figure 12a.

C. Tracer Studies

In evaluating possible impacts of the SC outfall discharge on the receiving coastal ocean environment, it is necessary to understand what contribution, if any, is made by the outfall discharge to a particular measurement result. For example, at a given location of interest in the coastal ocean, if an N+N concentration of 0.28 µm is measured, one might ask what part of the 0.28 µm arises from the outfall discharge and what part arises from other sources such as the Boynton Inlet or oceanic upwelling? Tracer studies help to answer this by addressing these two questions: for the conditions present at the time of the study, does the discharge plume does indeed reach the location of interest? If it does, what is the dilution which the discharge plume undergoes by the time it arrives at that location?

Given the considerations enumerated above and given that the broader FACE program is concerned with all the major contributors of substances to the coastal ocean and not just the outfalls, an improved understanding of the possible impact of the SC outfall is gained through an improved understanding of the possible contributions of the Boynton inlet. Accordingly, a tracer study was carried both for the Boynton inlet and for the SC outfall. The inlet tracer study was carried out first (22-February-2007) because it was anticipated that the prevalent ambient currents would transport the inlet plume out of the study area by the time of the start of the outfall tracer study (26-February-2007). Measurements showed that this was indeed the case.

i. South Central Outfall

Ambient Currents

A tracer study denoted the Florida Outfalls and Coastal Inlets Tracer Experiment (FOCITE-1), was conducted for the SC outfall between 26-February-2007 and 1-March-2007. The RD and SF6 dosage time series for the effluent plume are shown in Figure 13. Since the Dye and SF6 were injected at a constant rate, times of reduced effluent flow (viz., nighttime) resulted in corresponding times of increased tracer concentration. In addition, a significant travel time was required for the effluent to traverse from the point of tracer injection (the de-chlorination plant 1455 Lake Ida Road, Delray Beach, FL) to the end of the ocean outfall. Tracer injection into the SC effluent began at about 4PM local time on 26-February-2007 and continued to be injected for a total time of approximately 44 hours.

The ambient current field for the time period extending from midnight on 25-February-2007 to midnight of 2-March-2007 as recorded by the GSR-south ADCP is shown in Figure 14. In this figure, ambient current magnitude and direction are shown at various depths in the water column ranging from 3.5 meters beneath the surface to 15.6 meters beneath the surface. Based on past plume observations, the effluent plume, being positively buoyant (fresh water) was expected to occupy the upper third or so of the oceanic water column immediately upon exiting the outfall pipe. An example of this process is observed in the acoustic backscatter image of the SC effluent plume obtained in the October 2006 cruise (Figure 7). Also note from Figure 14, the ambient current over the whole water column is approximately unidirectional, so that the effluent plume transport is expected to be similar irrespective of which depth horizons the plume might occupy. Note that at the time of initiation of tracer injection that the ambient current is in transition from the north to the northwest to the west

and (weakly) to the south. This is a counter clockwise rotation of the current and is often associated with transient eddies.

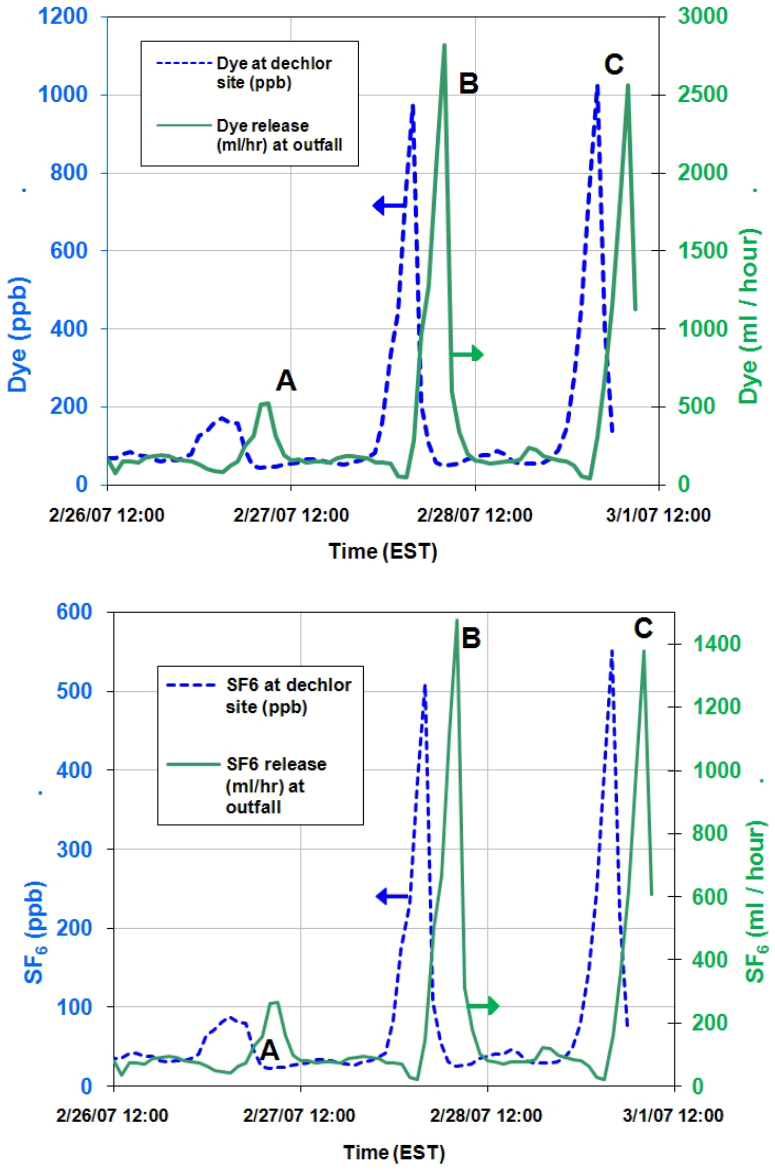


Figure 13. RD (upper panel) and SF_6 (lower panel) dosage into the SC effluent plume. Peaks in the concentration are denoted A, B, and C. The blue line denotes the concentration of tracer in the effluent stream at the dechlorination facility, while the green line denotes the volume of tracer passing through the outfall pipe in the hour ending at the plotted time.

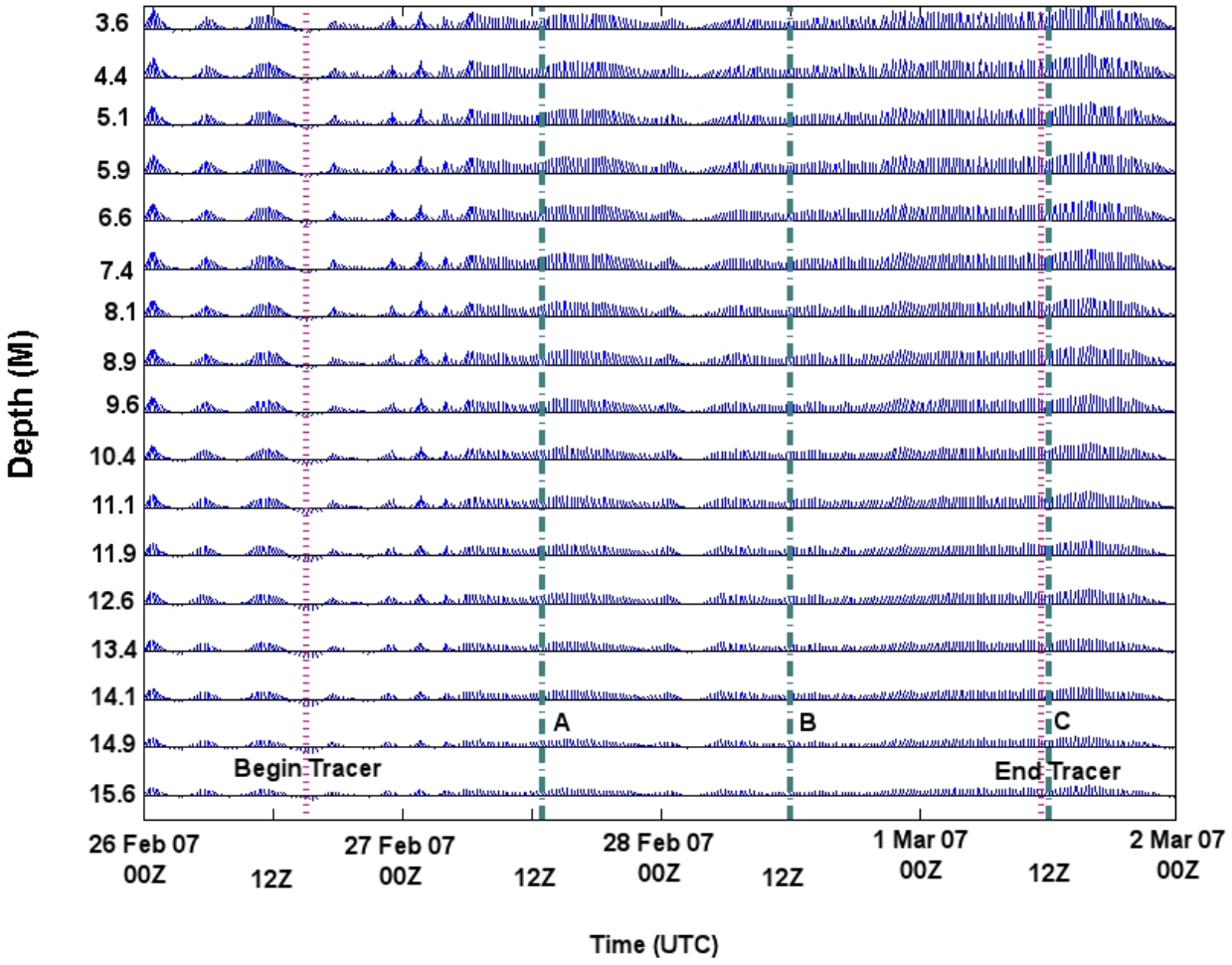


Figure 14. The ambient current field for the time period extending from 25-February-2007 to 1-March-2007 as recorded by the GSR-south ADCP. Red vertical lines mark the beginning and end of the FOCITE-1 dosing at the SC de-chlorination site. The letters A, B, and C refer to maxima in dosing shown in Figure 13.

Time Series Measurements

Measurements within one kilometer of the outfall

Shown in Figure 15 is the depth of the towed sensor/flow input device from decimal day 57.5 to 58 (GMT) (7:00 to 19:00 hours EST). The towed device ("Towfish") is a hydrodynamically-shaped towbody on which were mounted temperature, conductivity, RD, chlorophyll–a, and depth sensors. An intake nozzle for the SF6 is also mounted on the towbody. Water is pumped up from the towbody to the ship where SF6 analysis takes place. For the time period 57.55 to 57.65 GMT data from a high frequency ammonia analysis system also aboard the ship were recorded. Water samples pumped to the ship were split between the SF6 analysis system and the ammonia analysis system. The ammonia data shown were recorded before the dye contained within the effluent plume began to be detected and recorded.

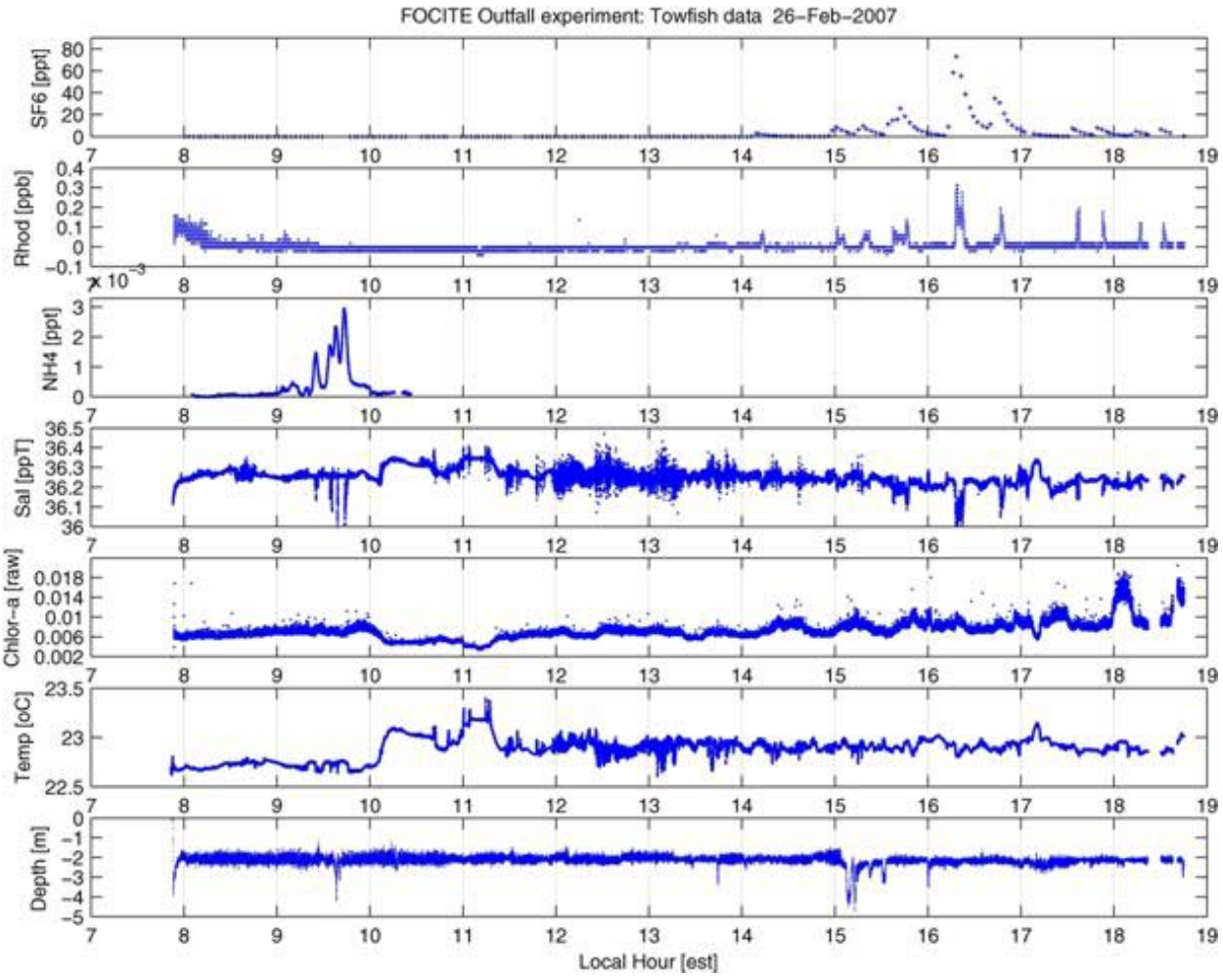


Figure 15. Towfish Data from 26-February-2007.

Figure 16 is an expanded view of the ammonium time series starting ~ 9 am in Figure 15 and the concomitant ship's track corresponding to the time of the ammonium data. These data are the first obtained from a new high-frequency, high-spatial-resolution, low-detection-limit, real-time ammonia

measurement device (Amornthammarong and Zhang, 2008). Measurements are made every five seconds and more than 80,000 ammonia measurements were made in the time period shown in Figure 30. In using this device, it is possible to map the spatial distribution of the ammonia field about the outfall.

Although a low level detection of RD and SF6 appears to have been made at 14:10 EST on that day, the first substantial detection of the outfall plume is made at 57.83 GMT (14:55 EST). The time series of RD and SF6 from 14:50 to 27:50 EST as well as the corresponding ship's track is shown in Figure 17. Both the ship's track and RD and SF6 time series are time labeled so that cross referencing of time series values and ship's position is possible. Consider the plume crossing occurring between 16:15 hours and 16:25 EST. As measured by RD the plume is contained entirely within this time interval. This peak is observed approximately 10.5 hours after initiation of dye injection.

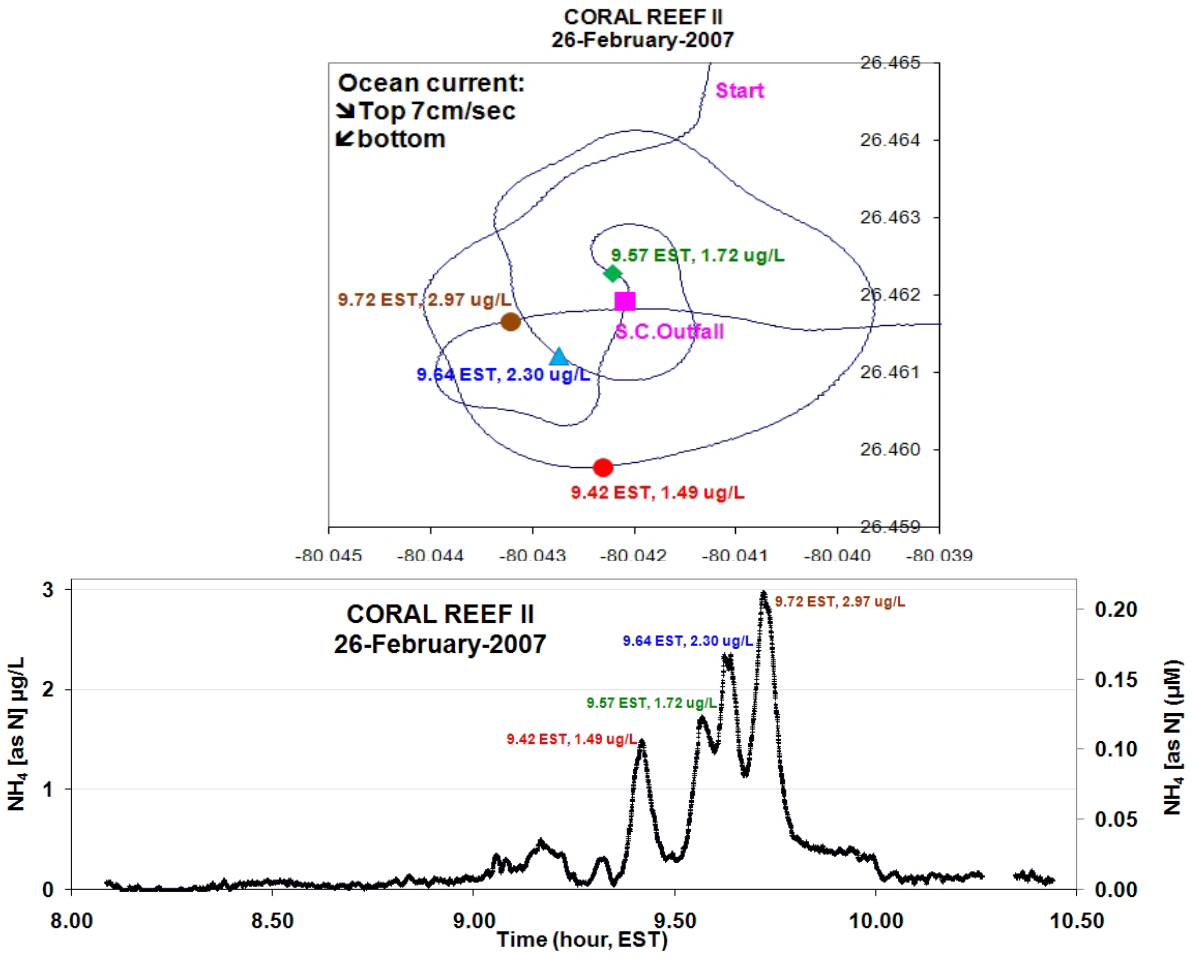


Figure 16. Ammonium measurements during FOCITE-1. Upper panel: track of Coral Reef II in the vicinity of the SC outfall, with locations of elevated ammonium concentrations denoted. Lower panel: plot of ammonium data versus time, with corresponding elevated ammonium peaks denoted with the same color.

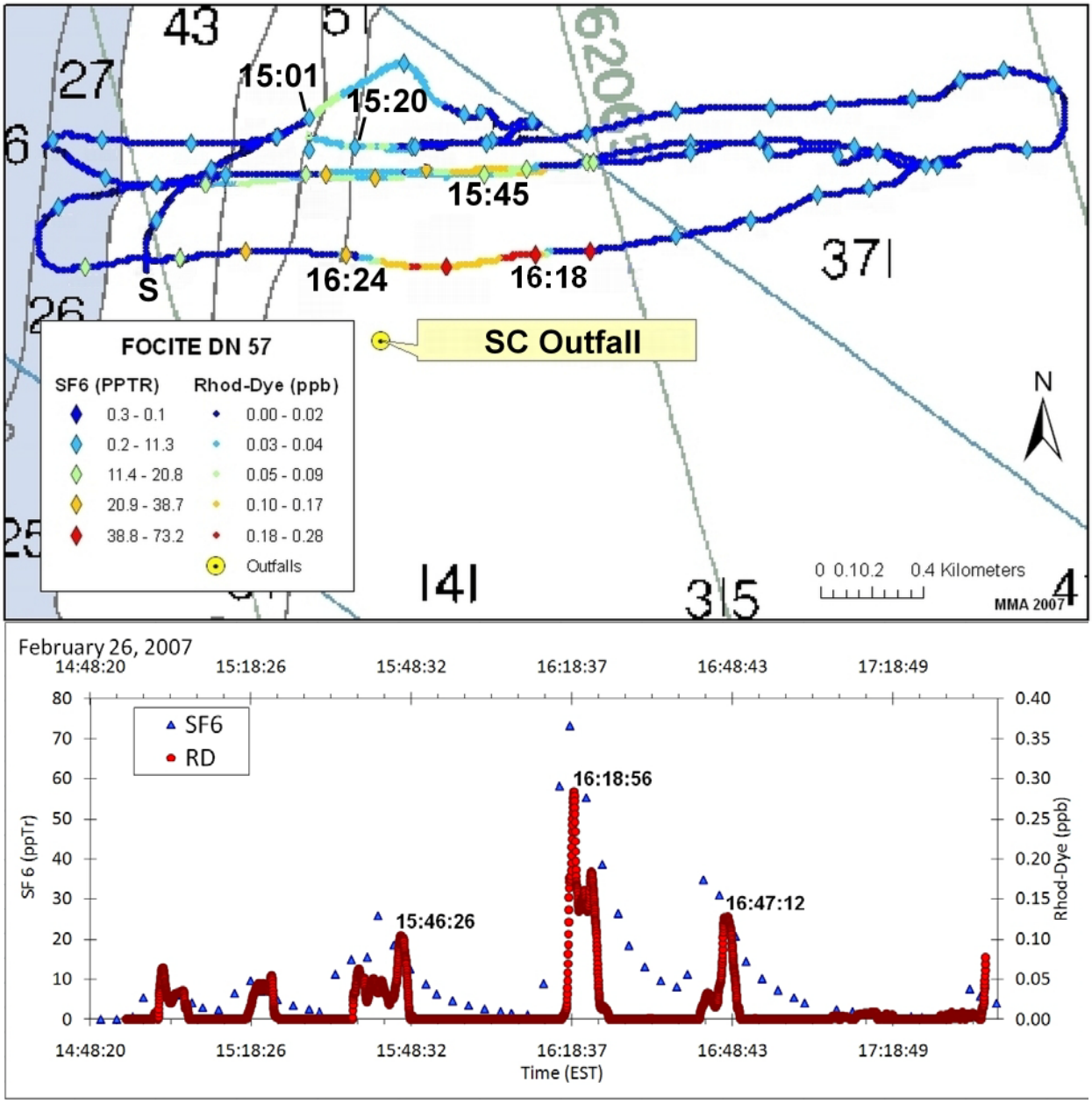


Figure 17. Dye and SF6 measurements during FOCITE-1. Upper panel shows track of the Coral Reef II for 26-February-2007, with colored lines denoting RD concentrations and colored diamonds denoting the SF6 concentration (beginning is denoted by "S"). Lower panel: Time Series of RD and SF_6 with time corresponding to the track in the upper panel. These data were obtained after that of Figure 16.

Prior to approaching the plume the RD registers a non-detection at 16:10 while the SF6 registers a low value of about one part per trillion. Both the RD and the SF6 registered a peak plume detection at approximately 16:18:14 EST. By 16:25 EST the RD value has reduced to approximately the non-detect level while the SF6 continues to register detections from the plume crossing until at least 16:35. Part of this continued detection by the SF6 system beyond the dye detection is due to the greater sensitivity of the SF6 and part is due to a instrument memory effect (due to hysteresis effects from travel time through the intake hose, mixing in the hose, and adsorption of SF6 onto sampling and extraction tubes), wherein SF6 is detected by the instrument after the ship has passed the tracer patch. Note that there is also an earlier detection of the plume by the SF6 as the plume is approached in the time interval 16:10 to 16:20 EST but no evidence of an extended ramping up to the plume peak as there is an extended ramping down from the plume peak. These features are seen in other plume crossings as well.

The dilution achieved by the plume at 16:20 may also be estimated from the data shown in Figures 13 and 17. In terms of the dosage time series it can be seen that the dye level for the time period preceding 16:20 is approximately 50 ppb. Then 50 ppb divided by 0.3 ppb, yields a dilution of approximately 233:1. A dilution estimate can also be made from the SF6 data. From Figure 13 it can be seen that average dosage value of approximately 45,000 pptr (45 ppb) is present prior to the peak detection of Figure 17. Dividing 45,000 pptr by 75 pptr yields a dilution of 600:1 at a range of 400 meters from the outfall.

The peak detection occurring at 16:20 hours is made at a range of about 400 meters from the outfall. The detections occurring in the period 15:35 to 15:50 and 16:30 to 16:50 EST are at a range of approximately 700 meters from the outfall and are essentially overlapping detections.

Measurements greater than two kilometers from the outfall

The dilution and vertical mixing the effluent plume undergoes as a function of range from the outfall is of much interest. Data from the present study and data from past studies have shown that the effluent plume at the boil is generally, but not always seen to occupy the upper third or so of the water column. The key question is how does the effluent plume mix downward in the coastal ocean water column? Very little data exists regarding the vertical mixing which effluent plumes undergo in the South Florida coastal ocean. It must be borne in mind that effluent plume mixing, dispersion and dilution is a three dimensional problem and that dilution in all three dimensions must be observed. While one may anticipate that effluent plume mixing with depth will increase as a function of range from the outfall, it must be borne in mind that the plume also dilutes with range, so that a decreasing tracer signal for vertical mixing measurements will occur with increasing range. Also, plume structure at longer ranges is poorly known with little information on the variability of spatial plume concentration.

To address the vertical mixing with range question two approaches were utilized: the first was to select a series of ranges or distances from the outfall discharge site at which the research ship would be placed in a drift mode while the towbody described above would be lowered and maintained near the bottom, at mid-water depth, and finally near the surface for a period of time. A total of seven of these "casts" were performed on 27 and 28-February, and are shown in Figure 18.

The second method involved the placement of two RD measuring fluorometers about 3 km from the outfall (approximately the southern limit of the GSR) so that within the detection limit of the devices vertically dispersed effluent dye tracer would be detected. These data will be described in the next section.

We examine two casts in detail; these are denoted “A” and “B” in Figure 18. Shown in Figure 19 are time series data for depth, RD, SF6, temperature, salinity and Chlorophyll-a obtained on 27-February-2007, 6 to 7 pm EST and in Figure 20, for 28-February-2007, 11 to 12 EST, 2007 (“B”). In the right-hand panel of the figures, the blue line denotes the drift of the ship’s position during the cast; for cast “A” the drift is about 3.7 km. Note that the SF6 value recorded decreased from approximately 18 pptr to about 4 pptr in going from a towbody depth of 2 meters to a towbody depth of 15 meters. When the towbody was raised a surface value of 40 pptr was recorded. Similar results were obtained for the other casts during 28-February (Figure 18), as the towbody was lowered that the SF6 detected level reduced with depth from its value near the ocean’s surface. The apparent dilution undergone by the effluent plume from ocean surface to 15 meters is about 18:4 (4.5:1) for the downgoing towbody and 40:4 (10:1) for the upgoing towbody. For the RD data a surface value of about .06 ppb is recorded while a lower value of less than 0.01 ppb is recorded. Shown in Figure 20 is an expanded view of the “B” cast.

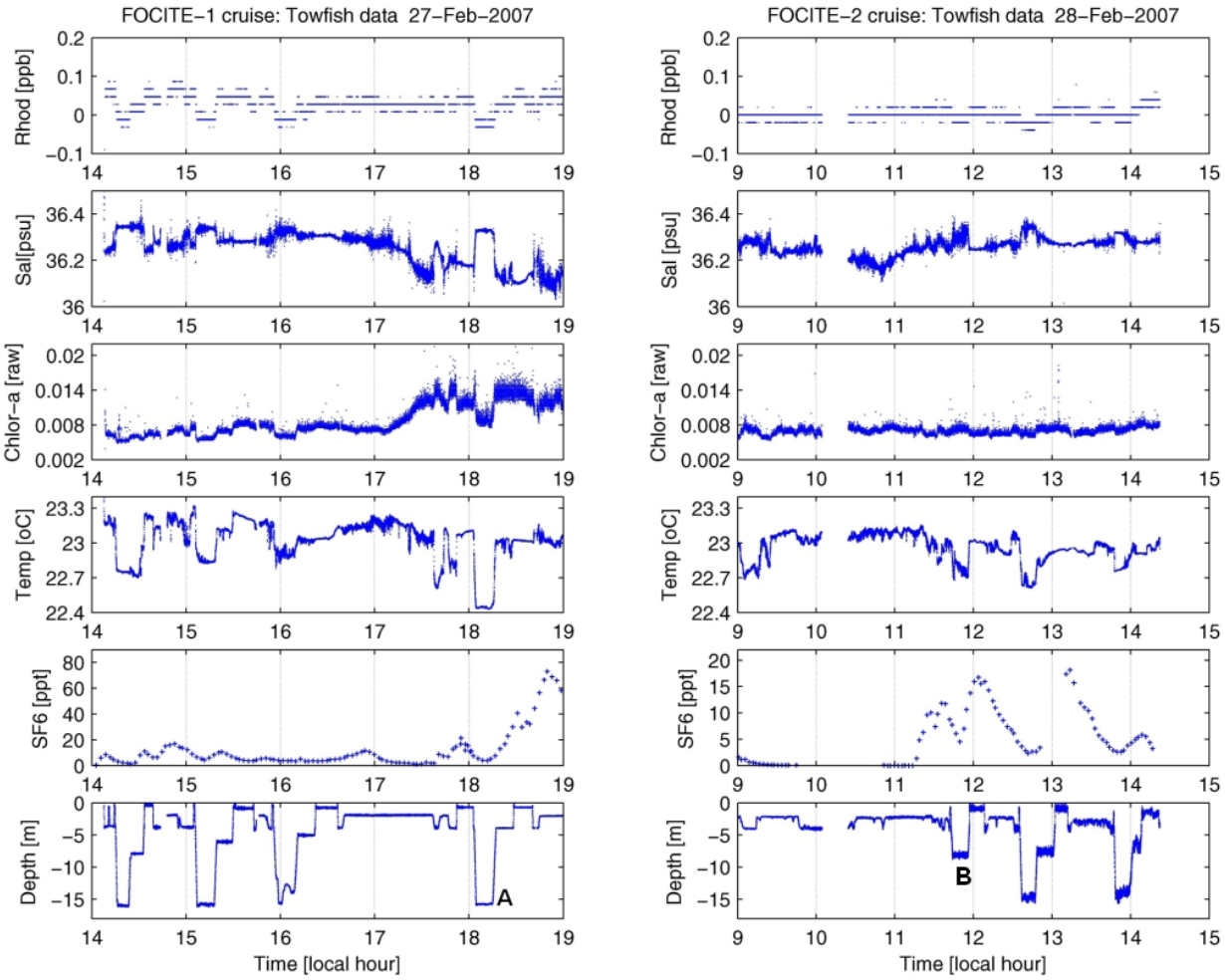


Figure 18. Time series for depth, RD, SF6, temperature, salinity, and Chlorophyll-a obtained on 27-February-2007 (left panel) and 28-February-2007 (right panel).

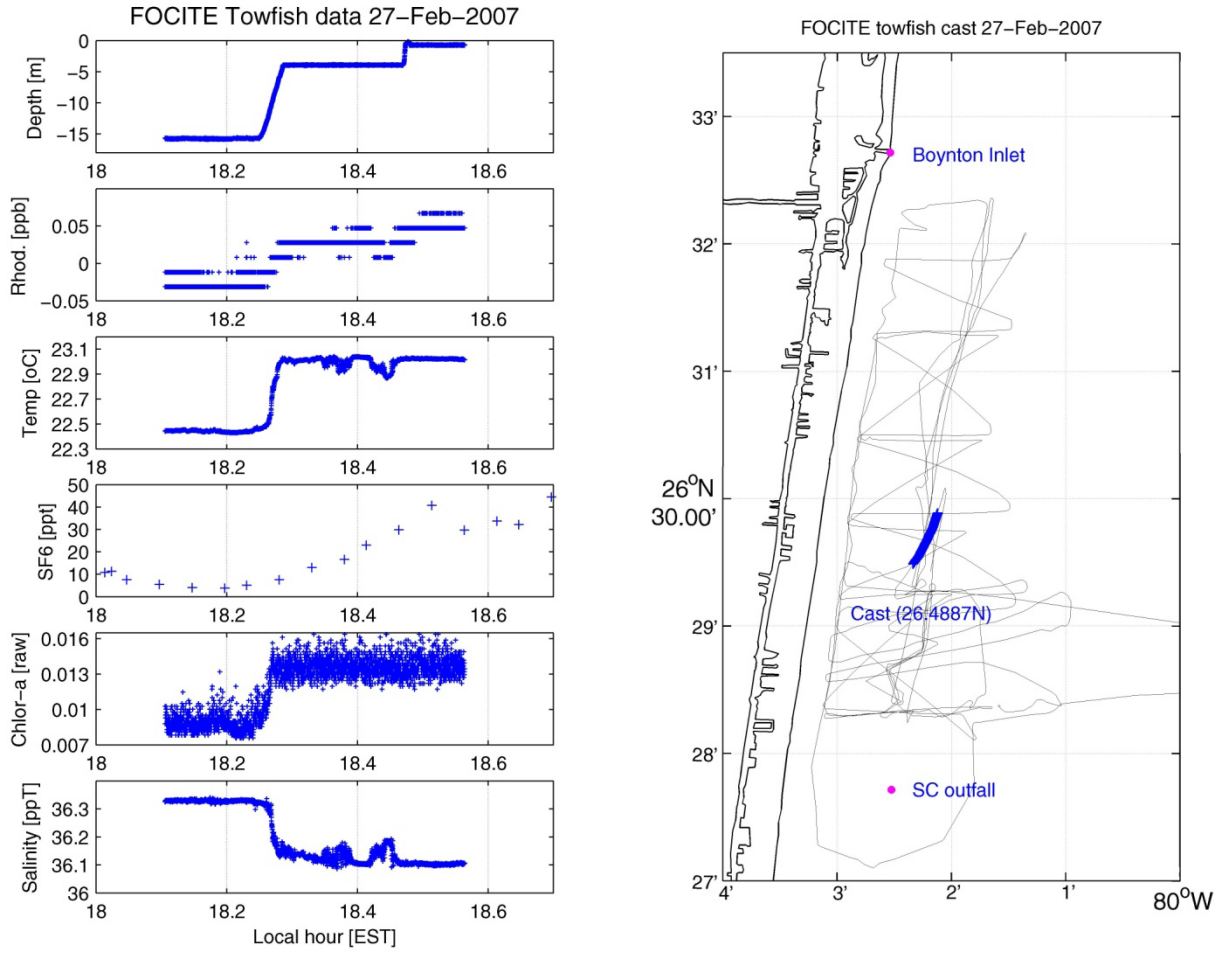


Figure 19. Expanded view of cast 'A' in Figure 18: time series data (left panel) and ship track (right panel) between 58.96 and 58.985. In the right panel, the highlighted track line denotes the ship movement (~0.83 km) during the indicated time interval.

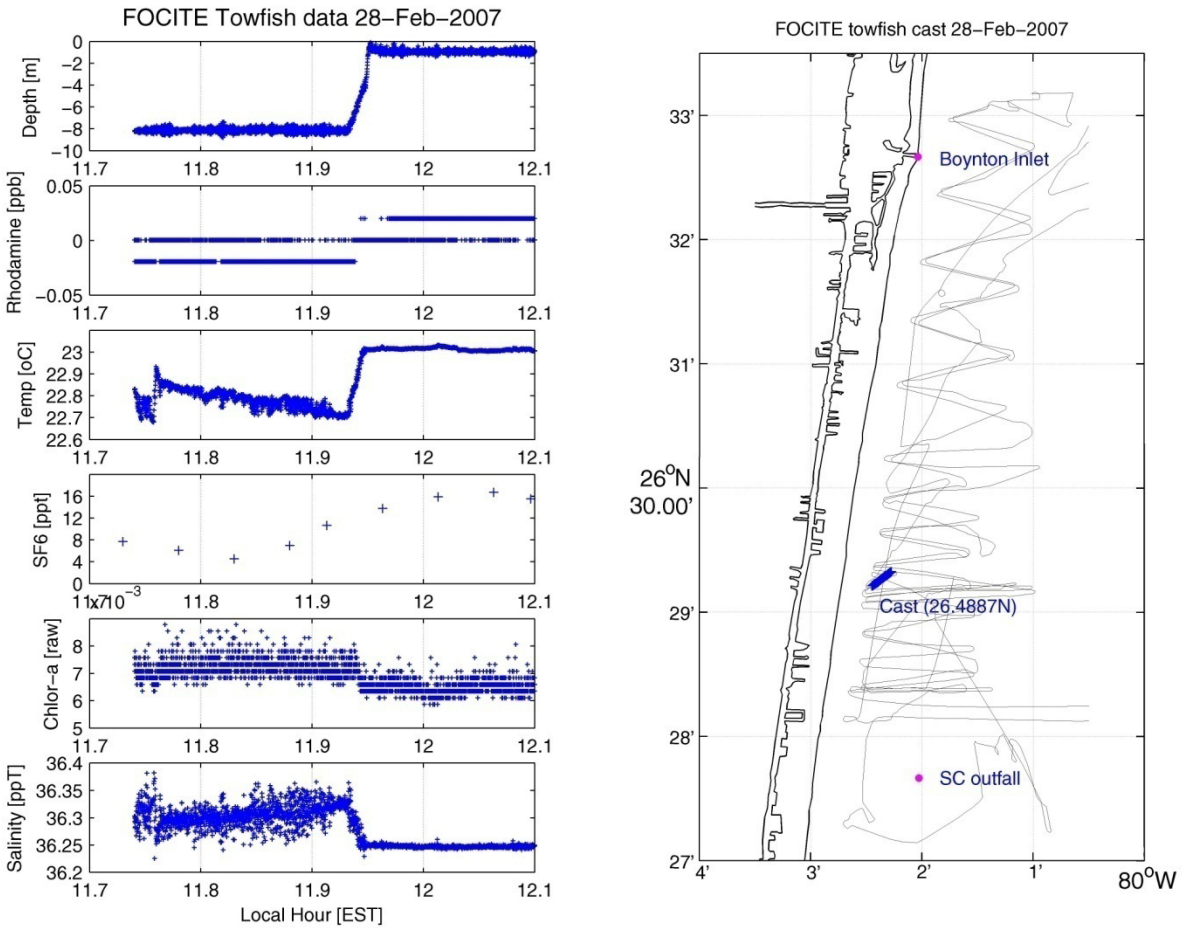


Figure 20. Expanded view of cast 'B' in Figure 18: time series data (left panel) and ship track (right panel) between 59.70 and 59.71. In the right panel, the highlighted track line denotes the ship movement (~0.36 km) during the indicated time interval.

YSI data

During the 2007 FOCITE-1 experiment, two multichannel underwater analysis instrumentation units (YSI model 6600, Yellow Springs, Ohio) were installed at a location (26° 29.27'N, 80° 2.32' W) very near the SGR-south ADCP and ~2.9 km northeast of the SC outfall (Figure 2). One instrument was located near the sea floor (depth ~17 m); the second was tethered at a depth of ~10 m. The instruments measured temperature, salinity, RD, chlorophyll-a, and pressure (depth). The instruments were installed on 16-February-2007 and removed on 11-March-2007. The resulting data is shown in Figure 21a (mid-level mount) and Figure 21b (bottom mount). Examination of the data indicates that the data degraded with time, probably due to bio-fouling, especially at the mid-level location after ~day 59 (28-February).

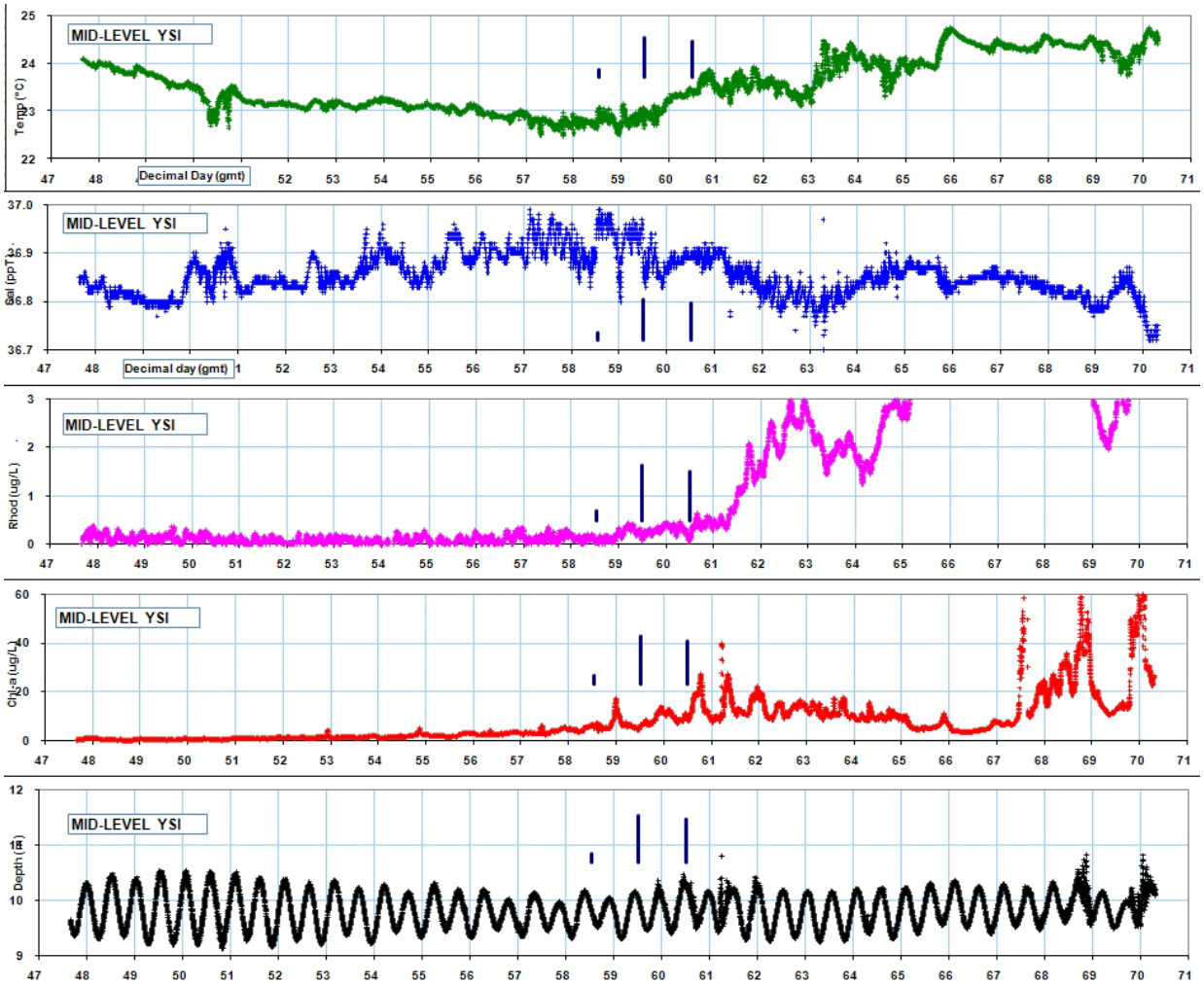


Figure 21a. Record of the mid-level YSI data from 16-February-2007 (day 47) to 11-March-2007 (day 70), showing temperature (top panel), salinity (second from top), RD (third panel), chlorophyll-a (fourth panel), and depth (bottom panel). The YSI data is recorded every two minutes. To reduce instrument noise, running averages are plotted here for RD (41 data points) and for chlorophyll-a (21 data points). The vertical bars mark the time and relative intensity of the three maxima of tracer from the SC outfall (*c.f.* Figure 13).

A major goal of the YSI deployments was to determine if any RD could be detected at that site. Because the plume was made of fresh (buoyant) water, observation of dye at mid or bottom depth would indicate substantial downward mixing of the plume. As the YSI units were mounted ~2.9 km north of the outfall, the measured average velocity (V-component) of ~33 cm/sec (from GSR-north) results in an estimated transit time of ~2.4 hours or 0.1 days from the outfall to the YSI. While there may be significant degradation of the mid-level fluorometer data due to bio-fouling, nevertheless, for either unit, there is *no apparent no dose-related signal in the RD data* corresponding to the three concentration spikes of RD introduced into the generally northward current from the outfall pipe. It is evident that the RD from the outfall plume was not able to mix downward to the depth of ~ten meters during the transit from the pipe to the instruments.

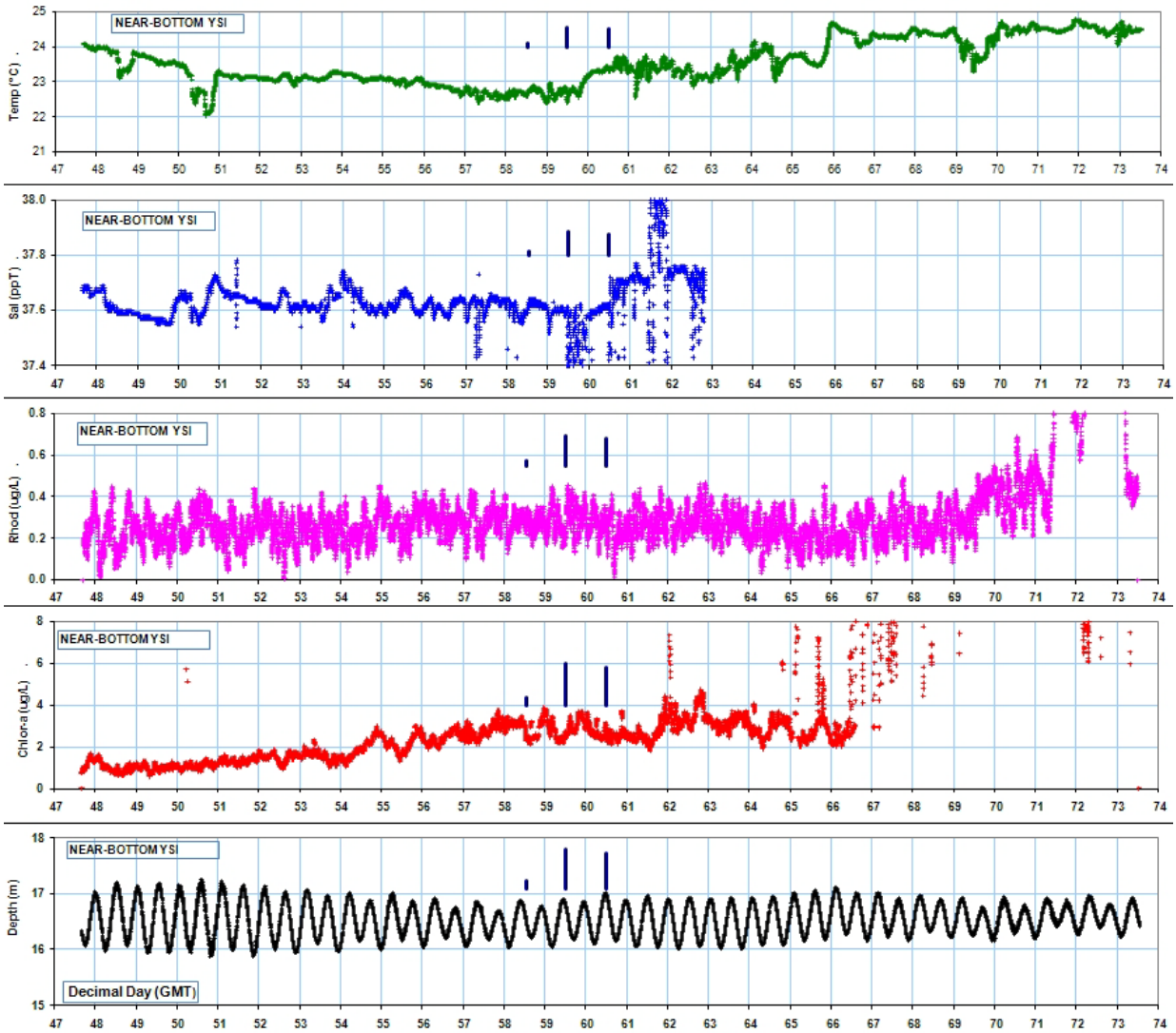


Figure 21b. Record of the bottom-mounted YSI data from 16-February-2007 (day 47) to 14-March-2007 (day 73). Presentation details are similar to Figure 22a. The salinity capability of the YSI failed during day 62.

ii. Boynton Inlet Tracer Study

The Boynton inlet study occurred prior to the SC outfall study, as previously noted. Apparatus was assembled on the south side of the inlet to provide for concurrent dosings of SF6 and RD early on 22-February-2007, from 1:58 am to 5:05 am EST, during the outgoing flow through the inlet (Figure 22). The RD was detected using the Towfish device described above (p. 26) from the R/V Coral Reef. The Towfish was fitted with sensors for the measurement of RD, sea water temperature, salinity

(conductivity), turbidity, Chlorophyll-a, and depth (pressure). The ship was piloted to execute a series of crisscross transects at various ranges from the inlet mouth. The plume could be tracked for more than fifty miles from the inlet. The ship's track with recorded values of SF6 is shown in Figure 23 (left panel) for 24-February-2007.

Figure 22: View of Boynton Inlet (GoogleEarth). The approximate location of the dosing pipe is indicated by the red "X", at 26°32'45" N, 80°2'38"W.

Also shown in Figure 23 are the time series of RD, SF6, and Chlorophyll-a data for February 24. Note that peaks are concurrently observed in the two data time series history. Note also that a "tail" appears in the SF6 data, but not in the RD data. The tail is caused by a purge time effect in which SF6 gas temporarily trapped in the hose and other system components continue to be released after the ship has already passed through actual dye in the water column. This effect has the consequence that the spatial extent of the inlet plume is extended.

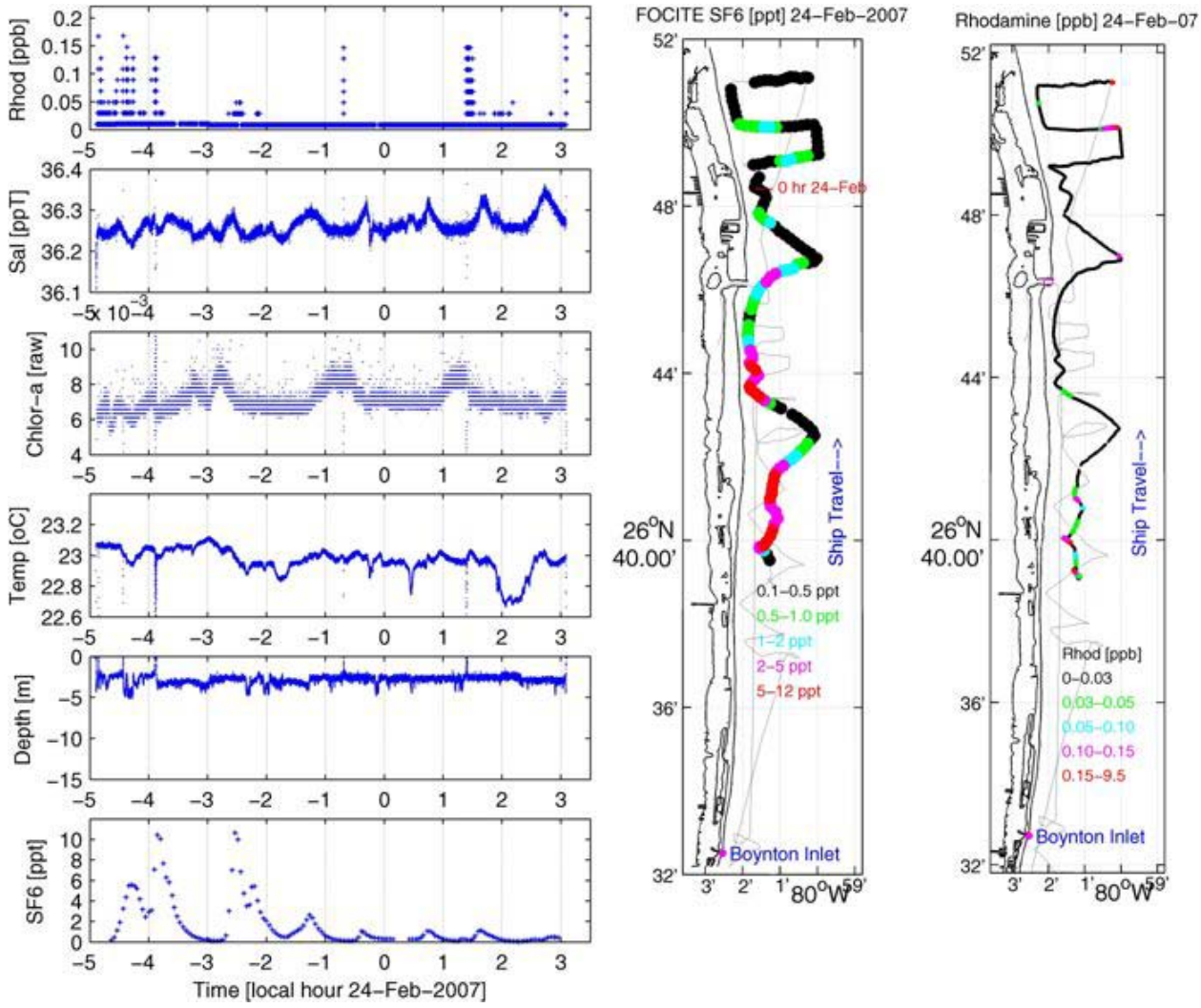


Figure 23. Left: data time series of RD, salinity, chlorophyll-a, temperature, depth, and SF6 for 24-February-2007. Right: Ship's track with recorded values of SF6 and RD.

D. Boynton Inlet 48 Hour Intensive studies

Two forty-eight hour intensive studies of the Boynton Inlet were carried out, on September 26-28 and June 4-6 of 2007. Measurements obtained during these studies included dissolved nutrients (N+N, phosphate, silicate, ammonium), a variety of microbiological markers, total suspended solids (TSS), temperature and salinity. Flow through the inlet was measured using a side-looking ADCP, which provided a measurement every 15 minutes. The flow through the inlet is controlled by the tides, so that there are two outbound (ebb) and two inbound (flood) cycles each day (eight ebb and eight flood flow pulses during the two intensives).

During flood tide, the water was coastal marine water and was found to be quite low in nutrients; however, the ebb tidal flow was characterized by elevated nutrients and microbiological markers, and was seen to be highly colored (probably due to tannic acid). Figure 24 is a plot of the flow and nutrient data for the two intensives. From the nutrient concentrations and flow measurements, the flux of

material exiting the Inlet into the coastal ocean can be computed. These data are shown in Table 5, averages and plotted in Figure 25. These results indicate that the outgoing tide contains significant concentrations of NO3, NO2, phosphate, ammonia, and especially silicate. Indeed the nutrient loading per day through the Inlet, for the time period of measurement, exceeds that of the SC outfall. (Phosphate measurements were obtained during the June Intensive but are not shown because of possible contamination of the samples).

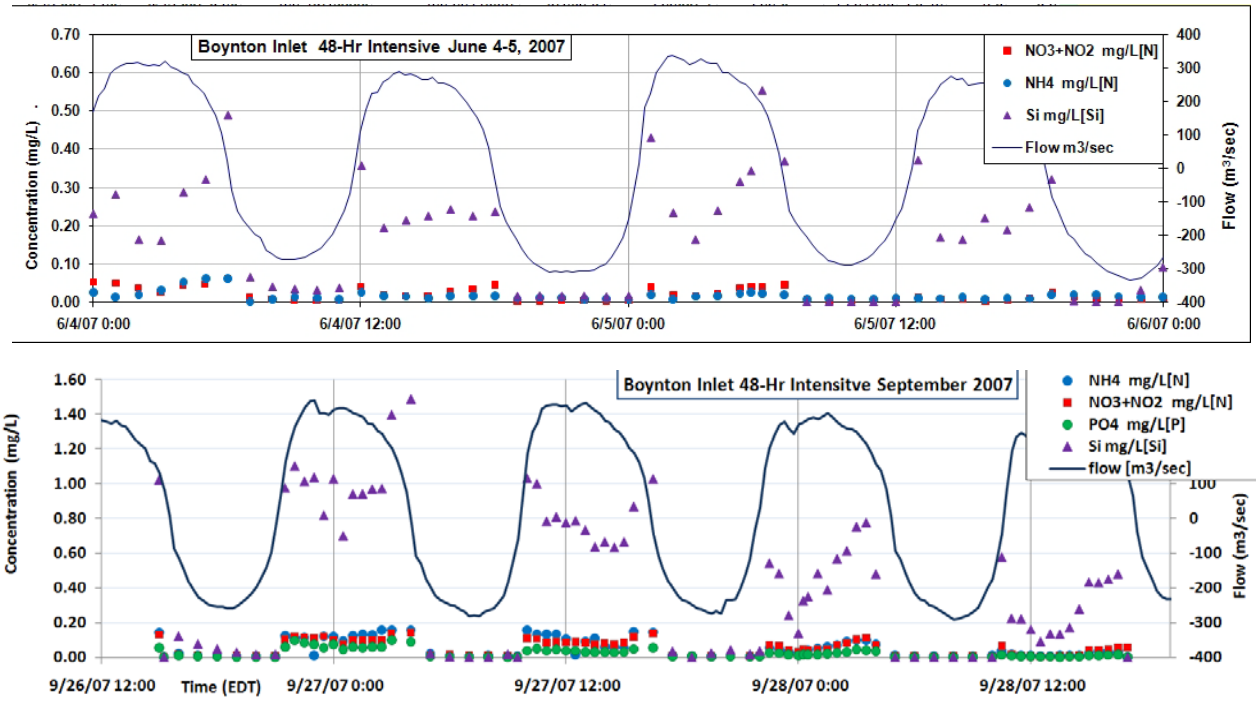


Figure 24. Inlet flow, nitrate (NO3) plus nitrite (NO2), and ammonia time series data for the June 2007 intensive (upper panel) and the September intensive (lower panel).

Table 5. Net mass [kg] of nutrients into the coastal ocean for eight ebb tide (out-flowing) pulses.

Nutrient	June 2007				September 2007					
	1	2	3	4	1	2	3	4	Ave	StDev
N+N [as N]	204	99	138	23	599	476	3303	78	240	205
Si [as Si]	1196	955	1452	798	5255	4134	2248	1215	2157	1652
PO_4 [as P]					362	195	116	31	176	141
NH_4 [as N]	171	68	89	41	599	524	286	78	232	218

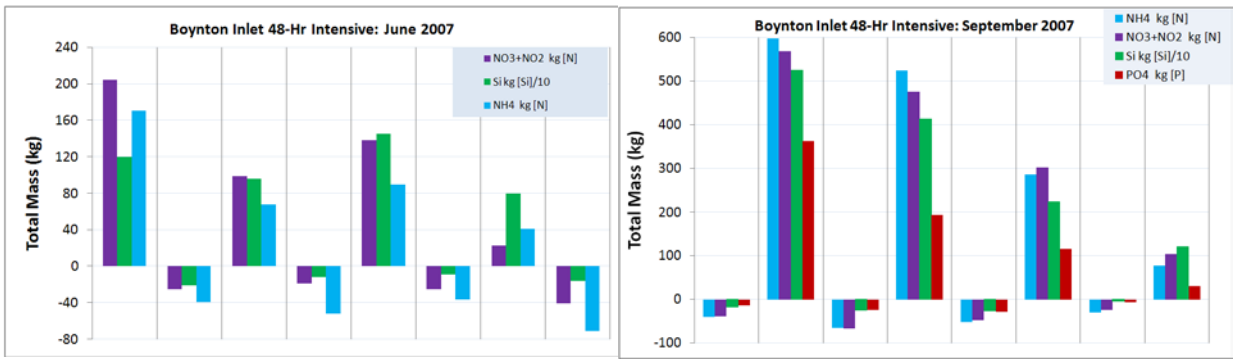


Figure 25. Net out-flowing and in-flowing masses for the June (left panel) and September (right panel) intensives. Positive values refer to outgoing (ebb tide) concentrations; negative values are incoming (flood tide) concentrations. Note that Si concentrations have been divided by 10.

Although the ebb tide *flow* out the Inlet is about the same for the eight pulses (Figure 24), considerable variation in out-flowing nutrient *masses* for the eight ebb tide pulses should be noted. In almost every case, nutrient concentrations in flood tides are low but in ebb tides are quite elevated. Secondly, the quantities of out-flowing masses in the June intensive are considerably lower than in September. Lastly, all four analytes show dramatic decreases during the September intensive.

To elucidate these observations, we will need to examine inputs into the Lake Worth Lagoon prior to the intensives. Rainfall from the vicinity of the Lagoon (DBHYDRO sites #16674, 16583, and 16675) is shown in Figure 26. Significantly, a very strong rain event occurred on 2-June-2007, dropping over eleven cm of rain which resulted in a large total canal flow on that day. By the time of the intensive on 4-June, the low levels of the N+N and NH4 may be indicating a 'washing out' of those nutrients in the lagoon, with silica and phosphorous remaining. Evidently, silica was still in suspension on the first outgoing ebb tide of the June intensive. For the September intensive, rain was present up the beginning of the Intensive, so that the 'washing out' of the nutrients is still in progress.

The overall view presented is that the lagoon input into the Inlet may be substantial but is also highly variable.

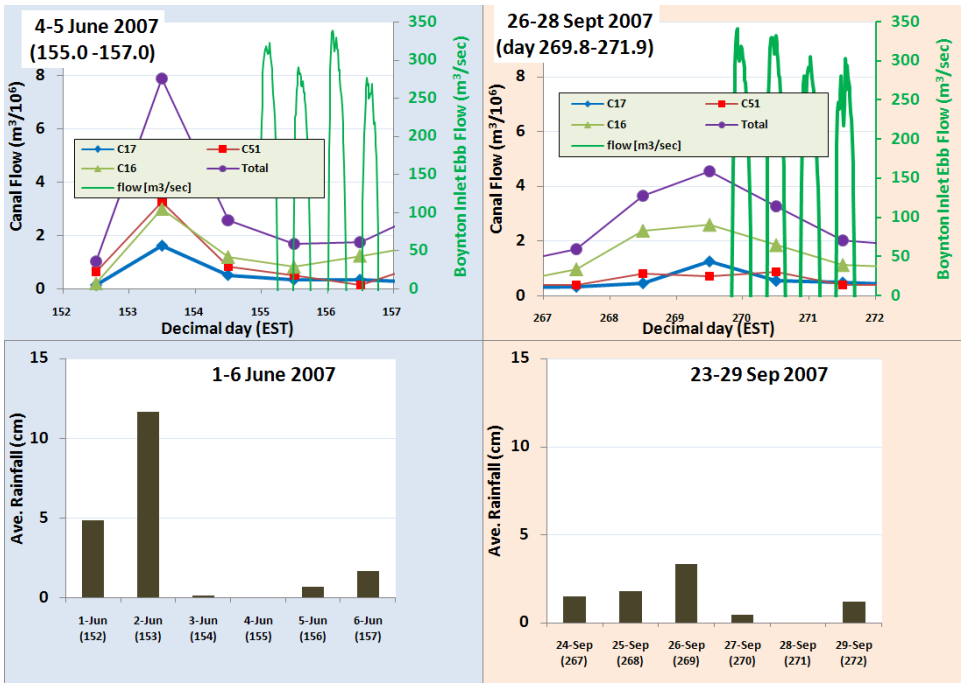


Figure 26. Rain (lower panels), canal (C16, C17, C51, and total) and inlet ebb tide water flow (upper panels) for June (left panels) and September (right panel) intensives. Green lines indicate ebb tide flow through Inlet during each intensive. Flow and rain data are from FDEP (DBHYDRO).

Microbiological data were also obtained. Results for the September intensive are given in Table 6. Table 7 shows approximate ocean currents during the two studies.

Table 6. Microbiological analysis results.

Detections of the following from the Boynton Inlet tidal cycles:	**Outgoing Tide**	**Incoming Tide**
live enterococci fecal indicator bacteria above US EPA recommended levels	**1** in 5 tides (52 cfu / 100 mL)	**None** in 5 tides
Human-source enterococci fecal indicator bacteria	**2** in 5 tides	**None** in 5 tides
Human-source *Bacteriodes* fecal indicator bacteria	**4** in 5 tides	**1** in 5 tides
Pathogenic gastrointestinal bacteria (salmonella, E coli O147:H7, and Campylobacter jejuni)	**None** in 5 tides	**None** in 5 tides
Potentially pathogenic drug-resistant ***Staphylococcus aurens***	**3 in 5 tides**	**None** in 5 tides
pathogenic protozoan **Cryptosporidium oocysts**	**3 in 5 tides (2.4, 6.3, and 24.9 cysts / 100 L)**	**None** in 5 tides
pathogenic protozoan **Giardia cysts**	**3 in 5 tides (1.2 4.2, and 19.4 cysts / 100 L)**	**None** in 5 tides
Human Adenovirus	**3 in 5 tides**	**1** in 5 tides
Human Noroviruses	**2 in 5 tides**	**None** in 5 tides
Human Enteroviruses	**2 in 5 tides**	**None** in 5 tides

Table 7. Approximate Ocean Currents during the two Boynton Inlet intensive studies

Study	Start Time	End Time	Approx. Dir. Of Ocean Current
June	6/4/2007 0:00	6/6/2007 0:00	North~100%
September	9/26/2007 12:00	9/28/2007 18:00	Mostly North with transitional period on 12 intervals

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IV. Discussion

The ambient current, water quality sampling, and tracer study information are required to understand the potential exposure which resources in the coastal ocean, such as coral reefs, may undergo to an effluent plume such as the SC plume. Water quality sampling serves to help determine the spatial distribution of nutrients about the outfall and whether spatial gradients traceable to the outfall

discharge site exist in said nutrients and other constituents. Presumably the distribution of nutrients is indicative of longer term water column and bottom nutrient patterns. To further examine longer term distributions of nutrients Dr. Peter Swart at the University of Miami carried out isotopic ratio studies of nitrogen and carbon in bottom sediments, the oceanic water column and algal tissues of all six outfalls (Swart and Drayer, 2008); their study found that the $\delta^{15}N$ in NO3 showed no evidence of isotopically positive $\delta^{15}N$ in the algal samples, although the most positive $\delta^{15}N$ values in the sedimentary organic material were associated with some of the outfalls. In a related project, Dr. Tony Shearer and co-workers at the Georgia Institute of Technology investigated stress gene expression patterns in nearby coral reef communities and found that the SC outfall plume did not contribute directly induce a genetic response in hard corals at Gulf Stream Reef (Shearer *et al.,* 2008).

A drawback in water quality studies is that in any given water quality sample analyzed it is difficult to attribute the sources of nutrients which may have contributed to the sample. In the case of the SC outfall other potential nutrient sources may exist including oceanic upwelling, the Boca Raton Inlet (about 14 Km south of the SC outfall site), the Boynton inlet (about 9 Km north of the SC outfall site), groundwater, and others.

A. Water Quality Samples

The distribution of sampling sites for the SC outfall is shown in Figure 11. Water column samples were obtained at three different depths (near surface, mid water column and near bottom) for each of the measurements sites in the coastal ocean. Consider first the N+N values measured and shown in Figure 12a. These data are from four of the six bi- monthly sampling cruises. For the June 2007 data the highest values are recorded in the Lake Worth Lagoon (BD 17) the coastal ocean measurements are low relative to the Lagoon measurements. To obtain a clearer view of the lower level of nutrients seen in June a second plot of the June data is made this time on an expanded scale. For the month of June 2007, it is seen that the majority of measurements made at sites BD 1 through BD 12 are less than 0.5 µM. The highest measurements recorded are site BD 1 south of the outfall site. The outfall boil may have been missed during the sampling since no elevated level was measured at the boil site.

Also shown in Figure 12a are the N+N values for August 2007. For August the highest N+N value, 8 µM, is recorded at site BD 4 in the upper part of the water column. The second highest coastal ocean site value is recorded at site BD 3 south of the outfall site. Once again a high N+N value is recorded in the Lake Worth Lagoon at site BD 17.

Of substantial interest is the spatial distribution and levels present of ammonia in the environs of the outfall site. The discussion of ammonia begins with the ammonia results for August 2007. The ammonia data are shown in Figure 12b. It may be seen from Figure 12b that the highest ammonia value recorded in August 2007 was at site BD 4, the outfall site, with a surface value of 22 µM. The next highest value was at site BD3, about 6 µM, south of the outfall. To examine the distribution of lower levels of ammonia measured, also shown in Figure 12b are the ammonia values on an expanded scale of zero to 2.5 µM.

An interesting question is whether the water column N+N distribution reflects the ambient current distribution. The ambient currents are 86% to the North and 14% to the south. Consider sites BD 3 and BD 5. These two sites bracket the outfall discharge site and are 0.43 km to the south and 0.49 km to the north of the outfall site respectively. The average N+N upper water sampling site (BD 3A) concentration for site BD3 for all six bi-monthly sampling cruises is 0.66 µM. For station BD 5A the average N+N concentration is 0.49 µM. For the mid-water column stations BD 3C and BD 5C the concentrations are 0.195 µM and 0.192 µM respectively. For the near-bottom sampling locations BD 3B and BD 5B, the concentrations are 0.245 µM and 0.21 µM respectively. In each case the average N+N concentration is higher at station BD 3 than at station BD 4.

B. Tracer Studies

Some discussion of the tracer studies has already been provided in section III c of this report. From Figures 20 and 21, it can be seen that both the RD tracer and the SF6 tracer indicate a decrease in concentration with depth. Near surface values have the highest dye and SF6 concentrations while the near bottom values have the lowest concentrations.

If a value of 4 pptr is utilized as the lower depth value for SF6, then additional vertical dilutions as great as 10:1 have been observed at ranges of 3.7 km from the outfall. However, because of the residual memory effects (see page 29), it may be that 4pptr is an overestimate of the SF6 concentration at depth. The SF6 system can register values below 4pptr if they are present. See for example the time period preceding the lowering occurring at about 18:00 on 27-February-2007. During this time period the ship has moved laterally out of the near surface plume with no change in depth of the towbody. As can be seen an SF6 value of zero is recorded. To address the question of the lower water column values of the SF6 water bottle samples were used in the recent (July 2008) tracer study. Results from this study will appear in the final report. The dye values at depth are at or below the detection limit of the dye. Nevertheless vertical dilutions of at least 6:1 are indicated by the dye.

To obtain some insight into how the vertical dilution impacts the total dilution at a specific range from the outfall, consider the dilution achieved at a range of approximately 3.7 km from the outfall on 27-February. From Figure 20 it can be seen that a peak at SF6 value of approximately 40 pptr is recorded very near the ocean's surface. At a depth of 15 meters an SF6 value of 4 pptr is recorded. The plume dilution at a depth of 15 meters is then given by 40,000 (the field values discussed here were obtained before the major SF6 peak "B" occurred) divided by 4 or 10,000:1. The surface dilution of 1000 seen in this example comports with the dilution calculated using the dilution with range equation given by Wanninkhof *et al.* 2005. Some questions remain with regard to the vertical dilution including: is the value of 4 pptr seen at depth the actual SF6 concentration value present in the water column or is the actual SF6 concentration less than 4pptr? This question arises because of the purge time required for the SF6 measurement system. To attempt to address this question, in the July 2008 cruise, water bottle sampling at various depths in the water column was utilized. The analysis of these samples is in process. A second question is while the calculation of total dilution (dilution relative to in pipe concentration) is straightforward; the dilution which takes place in going from the ocean surface to depth is affected by the spatial inhomogeneity of the SF6 concentration field at the ocean's surface. The ship drifts in the

ambient current so that the SF6 concentration near the surface at the time of initiation of the lowering of the intake hose is generally different from the near surface SF6 concentration upon completion of raising the intake hose from depth.

V. Conclusions for the South Central Outfall

A. Currents

1) The general flow of the ambient currents is north-northeast and south. About 86% percent of the time the flow is to the north.

2) The flow is generally unidirectional from near the ocean's surface to near the ocean's bottom.

3) The mean northward current speed tends to decrease with depth below the 3 meter depth. At the 3-meter depth the speed is ~32 cm sec^{-1}.

4) The eastward component of the current is fairly uniform with depth and decreasing as the surface and bottom are approached. The average current speed at the 3-meter depth is ~6 cm sec^{-1}.

B. Water Quality

5) The highest nutrient concentrations were usually found in the Lake Worth Lagoon and in the Boynton Inlet plume. In the SC boil, elevated concentrations were observed: 8.0 µM (N+N), 22.5 µM (NH4), 0.91 µM (P), and 4.4 µM (Si). Near-surface concentrations rapidly decreased north (south) of the outfall during northerly (southerly) flow, and became equal to the minimal concentrations found at the GSR and Inner sites within 3-4 km from the outfall. For example, N+N values measured away from the outfall site decreased with distance from the outfall with values as high as 0.8 µM occurring both north and south of the outfall. Near-bottom concentrations showed nearly zero influence from the outfall.

6) When a grand average over all six water quality sampling cruises and all three sample depths is computed for the quantities Silica, Phosphate, N+N, and Ammonium for each water quality site it is found that: (1) sites 6,7,8,and 10 spanning the GSR has an average N+N value of 0.17 µM. A value lower than all sites listed in Table 2 other than sites 11 and 12 just south of the Boynton Inlet, (2) Silica concentrations south of the outfall are substantially lower than those north of the outfall. Higher Silica concentrations are seen in the lagoon and Boynton Inlet.

7) The average concentration of N+N at site BD 3 located 0.43 km to the south of the outfall is approximately equal to the values of the N+N concentration at site BD 5 located 0.49 km north of the outfall for all three water column sampling depths. The average was computed over all six bi monthly sampling cruises.

8) The average ammonium concentration (0.45 μM) at sites 1 and 2 about 4.06 km and 2.26 km south of the outfall respectively are greater than the average ammonium concentrations (0.43 μM) at sites 6,7,8, and 10 (as a group in Table 4) which range in distance from 1.53 to 6.83 km from the outfall.

9) SUMMARY CONCLUSION: Based on the average N+N and NH4 concentrations listed in Table 4, the distribution of these quantities is not biased about the outfall location in the north-south direction. Silica concentrations are seen to be higher north of the outfall than south of the outfall. Silica concentrations north of the outfall are lowest at the GSR. Thus while ambient currents are to the north at approximately 86% of the time the N+N and NH4 values do not show a similar bias to the north of the outfall.

C. Tracer Studies

11) Measurements of tracer concentration have been made for the SC outfall at various ranges from the outfall. The dilution with range from the outfall as determined from upper water column samples comports with those measured earlier at the City of Hollywood outfall (Wanninkhof *et al.,* 2005). The earlier measurements of Wanninkhof *et al.* south of the Pt. Everglades inlet were made in the upper part of the water column.

12) Substantial spatial variability is observed in the near surface values of dye and SF6 tracers. The SF6 concentration is seen to vary from 18 pptr at the initiation of downcast A in figure 19 to a value of approximately 40 pptr at the termination of downcast A.

13) The dilution determined for the SF6 concentration values listed in (12) preceding are 2220:1 and 1000:1 respectively. (These dilution estimates are based on the estimate of an initial SF6 concentration of 40 parts per billion (ppb) or 40,000 parts per trillion (pptr). This initial concentration is based on flow estimates not on concentration measurements). For the approximately 75 pptr peak shown in figure 19, the dilution is estimated at 533:1.

14) Both the dye and SF6 tracers indicate a substantial reduction in concentration with depth

15) For the case of lowering A in figure 19, a level of 4 pptr was recorded at a depth of 15 meters For the three near-surface concentration values in 12) and 13) above, i.e. 18 pptr, 40 pptr and 75 pptr for a surface-to-bottom dilution of 4.5:1, 10:1 and 18.75:1. The concentration value of 4 pptr is likely to be an upper limit of the near-bottom SF6 concentration because of the memory effects referred to in section 3.C.i., thus the dilution may be even greater.

16) The dilution corresponding to the near-bottom concentration of 4 pptr may be estimated without reference to possible surface concentrations by dividing the estimated source value of 40,000pptr by 4 resulting in a dilution estimate of 10,000:1.

17) The near-bottom in-situ RD sensor placed on the GSR did not detect any RD in the course of the study; ambient currents were directed to the north during much of the study so that effluent plume material was transported in the direction of the reef area.

18) The mid-water column did not unambiguously detect RD, as there appeared to be degradation of the data due to bio-fouling which made it difficult to unambiguously identify dye signals.

19) Upper water column detections of RD were made by the ship-towed RD sensor systems in the area of the in-situ sensor site while no detection were being made by the near-bottom RS sensor.

20) SUMMARY CONCLUSION: Very little RD or SF6 made its way down to the GSR. This implies that very little, if any, effluent plume mixed to the bottom during the period of the tracer tracking study at the sensor site on the that reef.

VI. Summary

This present interim report presents data gathered not only in the study of the SC Outfall, but of other outfalls and the Boynton inlet as well. While the focus of this report has been principally on the outfall operated by the South Central Regional Wastewater Treatment and Disposal Board, data from other outfalls, the Boynton Inlet, and adjoining lagoonal areas have been utilized as well. A long standing question in the operation of south Florida oceanic outfalls has been whether the outfall's "impact" proximal coral reefs or other sites of interest including the oceanic water column. Two initial questions for determination of "impact" are: (a) Do the outfall effluent plumes make contact with the reefs and (b) what substances might be transported by the plumes to the reefs?

A well-known characteristic of the effluent plumes is that they are generally positively buoyant and typically rise to the ocean's surface to form a "boil". In coastal regions where stratified water columns may exist, such as Massachusetts Bay, effluent plume "detrainment" may occur so that subsurface horizons of plume material may be formed. The effluent plume and boils are subject to the ambient currents present in the south Florida coastal ocean.

The question of whether the effluent plume contacts the proximal reefs turns upon two principal considerations: (1) the distribution of ambient currents and (2) the (downward) vertical mixing of the effluent plumes. The question as to what substances are contained in the plume has as a corollary the questions: (3) what is the concentration of the substances and (4) what dilution has transpired?

The data presented in this report show that for the majority of the time the ambient current at the outfall flows to the north (slightly northeast) approximately 86% of the time at the SC outfall. There is however periods of time during which southerly directed flows occur. The data presented in this report also show that very little vertically downward mixing of the effluent plume transpired during the time frame of observations. This conclusion was reached during the tracer study period wherein both the SF6 and dye indicated low tracer concentrations at depth compared to tracer concentrations in the upper

part of the water column. The water quality measurements made both north and south of the outfall do not indicate significantly elevated concentrations of nutrients at sampling sites north of the outfall when compared to sampling sites south of the outfall. Silica values do display an asymmetry about the outfall location with higher silica values seen north of the outfall.

Face program studies determined the presence of two possible sources of N+N to the reefs proximal to the SC outfall: (1) the Boynton Inlet and (2) oceanic upwelling. The N+N values for both the Boynton Inlet and from nearshore deeper ocean sites implicated in oceanic upwelling (Smith 1983) are indicated in this report.

Acknowledgements

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Appendix. Sample values obtained at each of the outfalls as well as sites removed from the immediate boil areas, October 2006.

Nancy Foster Oct-06	Date	Site surface	mid	bottom	Latitude	Longitude	Depth (m)	Chlorophyll a (µg/L)	Phaeo (µg/L)	NO_3+NO_2 [N] (µM)	NO_2 [N] (µM)	NH_4-N (µM)	P (µM)	Si (µM)
Boca Raton Outfall	13-Oct	1a	1	a	26.3506	-80.054	0	0.706	0.209	1.13	1.3	3.45	0.455	1.9
Boca Raton Outfall	13-Oct	2a	2	a	26.3511	-80.0546	0	0.734	0.246	0.26	0.04	0.7	0.212	0
Boca Raton Outfall	13-Oct	3a	3	a	26.3512	-80.0541	0	0.774	0.243	0.99	1.11	3.18	0.508	1.88
Boca Raton Outfall	13-Oct	4a	4	a	26.3511	-80.0536	0	0.699	0.197	1.93	2.12	7.22	0.969	3.3
Boca Raton Outfall	13-Oct	5a	5	a	26.3515	-80.0543	0	0.644	0.176	0.49	0.46	1.85	0.31	0.75
Boca Raton Outfall	13-Oct	6a	6	a	26.3515	-80.0538	0	0.475	0.174	0.38	0.38	1.29	0.256	0.3
Boca Raton Outfall	13-Oct	7a	7	a	26.3515	-80.0535	0	0.388	0.126	0.15	0.1	0	0.121	0
Boca Raton Outfall	13-Oct	8a	8	a	26.352	-80.0543	0	0.618	0.187	0.44	0.38	1.08	1.15	0.51
Boca Raton Outfall	13-Oct	9a	9	a	26.352	-80.0538	0	0.619	0.206	0.22	0.13	0.48	0.315	0
Boca Raton Outfall	13-Oct	10a	10	a	26.352	-80.0534	0	0.752	0.233	0.27	0.2	0.68	0.234	0.07
Boca Raton Outfall	13-Oct	1b	1	b	26.3506	-80.054	13.71	0.714	0.191	0.35	0.03	0.96	0.077	0
Boca Raton Outfall	13-Oct	2b	2	b	26.3511	-80.0546	12.7	1.446	0.424	0.14	0.08	0.56	0.163	0
Boca Raton Outfall	13-Oct	3b	3	b	26.3512	-80.0541	13.6	0.745	0.208	0.18	0.09	0.61	0.15	0.01
Boca Raton Outfall	13-Oct	4b	4	b	26.3511	-80.0536	14.66	0.696	0.137	0.24	0.09	1.35	0.221	0.01
Boca Raton Outfall	13-Oct	5b	5	b	26.3515	-80.0543	12.65	0.608	0.214	0.14	0.1	0.24	0.131	0.04
Boca Raton Outfall	13-Oct	6b	6	b	26.3515	-80.0538	13.93	0.587	0.159	0.24	0.17	1	0.155	0.09
Boca Raton Outfall	13-Oct	7b	7	b	26.3515	-80.0535	14.63	0.666	0.245	0.14	0.09	0.23	0.141	0
Boca Raton Outfall	13-Oct	8b	8	b	26.352	-80.0543	13.03	0.619	0.156	0.21	0.16	0.21	0.204	0
Boca Raton Outfall	13-Oct	9b	9	b	26.352	-80.0538	13.73	0.575	0.215	0.23	0.1	0.42	0.197	0
Boca Raton Outfall	13-Oct	10b	10	b	26.352	-80.0534	14.63	0.607	0.230	0.17	0.1	0.33	0.059	0
Boca Raton Outfall	13-Oct	1c	1	c	26.3506	-80.054	27.43	0.561	0.204	0.21	0.05	0.6	0.156	0
Boca Raton Outfall	13-Oct	2c	2	c	26.3511	-80.0546	25.4	0.000	0.000	0.24	0.07	0.11	0.132	0.01
Boca Raton Outfall	13-Oct	3c	3	c	26.3512	-80.0541	27.2	0.561	0.182	0.23	0.08	0.33	0.14	0
Boca Raton Outfall	13-Oct	4c	4	c	26.3511	-80.0536	29.32	0.603	0.190	0.26	0.11	0.61	0.191	0.04
Boca Raton Outfall	13-Oct	5c	5	c	26.3515	-80.0543	25.3	0.617	0.165	0.25	0.1	0.26	0.131	0.04
Boca Raton Outfall	13-Oct	6c	6	c	26.3515	-80.0538	27.86	0.681	0.151	0.25	0.11	1.3	0.177	0.04
Boca Raton Outfall	13-Oct	7c	7	c	26.3515	-80.0535	29.26	0.639	0.186	0.25	0.1	0.09	0.209	0
Boca Raton Outfall	13-Oct	8c	8	c	26.352	-80.0543	26.03	0.653	0.201	0.21	0.1	0.55	0.206	0.04
Boca Raton Outfall	13-Oct	9c	9	c	26.352	-80.0538	27.46	0.594	0.176	0.3	0.13	0.33	0.165	0

Nancy Foster	Date	Site			Latitude	Longitude	Depth	Chlorophyll a	Phaeo	NO_3+NO_2 [N]	NO_2 [N]	NH_4-N	P	Si
Oct-06		surface	mid	bottom			(m)	(µg/L)	(µg/L)	(µM)	(µM)	(µM)	(µM)	(µM)
Boca Raton Inlet Deepwater Site (BRI)	13-Oct	b	b	b	26.3561	-80.0081	30	0.242	0.084	0	0	0	0	0.19
Boca Raton Inlet Deepwater Site (BRI)	13-Oct	c	c	c	26.3561	-80.0081	60	N/A	N/A	0.1	0.1	0	0	0.61
Boca Raton Inlet Deepwater Site (BRI)	13-Oct	d	d	d	26.3561	-80.0081	90	N/A	N/A	1.38	0.22	0	0	1.37
Boca Raton Inlet Deepwater Site (BRI)	13-Oct	e	e	e	26.3561	-80.0081	120	N/A	N/A	7.97	0.07	0	0.394	5.2
Boca Raton Inlet Deepwater Site (BRI)	13-Oct	f	f	f	26.3561	-80.0081	150	0.014	0.039	13.92	0.02	0	1.027	8.02
Mid deep-water cast (PEI)	13-Oct	a	a	a	26.1323	-80.0488	0	0.242	0.058	0.2	0.01	0	0	0.64
Port Everglades Inlet Deepwater Site (PEI)	13-Oct	b	b	b	26.1323	-80.0488	30	0.177	0.058	0.01	0	0	0	0.5
Port Everglades Inlet Deepwater Site (PEI)	13-Oct	c	c	c	26.1323	-80.0488	60	N/A	N/A	0.03	0.01	0	0	0.77
Port Everglades Inlet Deepwater Site (PEI)	13-Oct	d	d	d	26.1323	-80.0488	90	N/A	N/A	2.43	0.27	0	0.034	2.2
Port Everglades Inlet Deepwater Site (PEI)	13-Oct	e	e	e	26.1323	-80.0488	120	N/A	N/A	6.56	0.06	0	0.377	4.26
Port Everglades Inlet Deepwater Site (PEI)	13-Oct	f	f	f	26.1323	-80.0488	150	0.025	0.046	14.56	0.02	0	1.27	9.38
Broward Outfall	14-Oct	1a	1	a	26.2524	-80.0618	0	0.940	0.166	2.91	2.22	21.09	1.005	3.35
Broward Outfall	14-Oct	2a	2	a	26.2547	-80.0613	0	0.772	0.193	0.93	0.66	6.49	0.524	0.92
Broward Outfall	14-Oct	3a	3	a	26.2538	-80.0615	0	0.774	0.243	1.28	0.95	9.17	0.582	1.25
Broward Outfall	14-Oct	4a	4	a	26.2529	-80.0616	0	0.850	0.185	1.13	0.82	7.97	0.337	1.11
Broward Outfall	14-Oct	5a	5	a	26.2546	-80.0618	0	1.209	0.355	0.26	0.06	0.98	0	0
Broward Outfall	14-Oct	6a	6	a	26.2538	-80.0618	0	0.869	0.185	0.55	0.29	2.42	0	0.43
Broward Outfall	14-Oct	7a	7	a	26.2529	-80.062	0	0.699	0.226	1.5	1.05	9.79	0.533	1.63
Broward Outfall	14-Oct	8a	8	a	26.2545	-80.061	0	1.001	0.403	1.29	0.91	8.2	0.068	1.09
Broward Outfall	14-Oct	9a	9	a	26.2537	-80.0611	0	1.072	0.438	0.36	0.21	1.33	0	0
Broward Outfall	14-Oct	10a	10	a	26.2529	-80.0613	0	1.093	0.556	0.12	0.03	0	0	0
Broward Outfall	14-Oct	11a	11	a	26.2514	-80.0619	0	1.811	1.039	0.24	0.07	0	0	0
Broward Outfall	14-Oct	1b	1	b	26.2524	-80.0618	16.75	1.050	0.137	0.59	0.38	3.82	0.517	0.38
Broward Outfall	14-Oct	2b	2	b	26.2547	-80.0613	17.5	0.804	0.112	0.54	0.33	3.75	0.446	0.43
Broward Outfall	14-Oct	3b	3	b	26.2538	-80.0615	17.58	1.408	0.490	0.12	0.01	0.82	0.184	0
Broward Outfall	14-Oct	4b	4	b	26.2529	-80.0616	17.26	0.732	0.146	1.12	0.8	8.24	0.249	1.09
Broward Outfall	14-Oct	5b	5	b	26.2546	-80.0618	16.27	0.779	0.140	0.29	0.14	1.73	0	0
Broward Outfall	14-Oct	6b	6	b	26.2538	-80.0618	16.46	0.692	0.149	0.36	0.15	1.55	0	0.02
Broward Outfall	14-Oct	7b	7	b	26.2529	-80.062	16.21	0.511	0.130	0.78	0.5	4.1	0	0.87
Broward Outfall	14-Oct	8b	8	b	26.2545	-80.061	19.38	1.148	0.385	0.2	0.04	0	0	0
Broward Outfall	14-Oct	11b	11	b	26.2514	-80.0619	17.08	1.137	0.448	0.39	0.22	1.28	0	0
Broward Outfall	14-Oct	1c	1	c	26.2524	-80.0618	33.5	0.649	0.157	0.26	0.05	0.24	0.38	0
Broward Outfall	14-Oct	2c	2	c	26.2547	-80.0613	35	0.459	0.125	0.2	0.02	0.78	0.355	0.16

Nancy Foster	Date	Site			Latitude	Longitude	Depth	Chlorophyll a	Phaeo	NO_3+NO_2 [N]	NO_2 [N]	NH_4-N	P	Si
Oct-06		surface	mid	bottom			(m)	(µg/L)	(µg/L)	(µM)	(µM)	(µM)	(µM)	(µM)
Broward Outfall	14-Oct	3c	3	c	26.2538	-80.0615	35.17	0.452	0.035	0.2	0.02	0.88	0.065	0.13
Broward Outfall	14-Oct	4c	4	c	26.2529	-80.0616	34.53	0.380	0.060	0.25	0.06	0.36	0	0.21
Broward Outfall	14-Oct	5c	5	c	26.2546	-80.0618	32.55	0.397	0.112	0.27	0.07	0.36	0	0.19
Broward Outfall	14-Oct	6c	6	c	26.2538	-80.0618	32.92	0.317	0.105	0.29	0.09	0.66	0	0.35
Broward Outfall	14-Oct	7c	7	c	26.2529	-80.062	32.43	0.391	0.113	0.29	0.06	0	0	0.21
Broward Outfall	14-Oct	8c	8	c	26.2545	-80.061	38.77	0.345	0.077	0.26	0.07	0	0	0.46
Broward Outfall	14-Oct	9c	9	c	26.2537	-80.0611	38.4	0.482	0.121	0.26	0.07	0.03	0	0.24
Broward Outfall	14-Oct	10c	10	c	26.2529	-80.0613	37.76	0.579	0.107	0.24	0.03	0	0	0
Broward Outfall	14-Oct	11c	11	c	26.2514	-80.0619	34.17	0.628	0.148	0.25	0.08	0	0	0
South deep-water cast (MCI)	15-Oct	a	a	a	25.7432	-80.062	0	0.166	0.042	0.09	0.04	0	0.05	0.46
Miami Central Inlet Deepwater Site (MCI)	15-Oct	b	b	b	25.7432	-80.062	30	0.173	0.052	0.05	0.03	0	0.032	0.3
Miami Central Inlet Deepwater Site (MCI)	15-Oct	c	c	c	25.7432	-80.062	60	N/A	N/A	0.28	0.26	0	0.043	0.54
Miami Central Inlet Deepwater Site (MCI)	15-Oct	d	d	d	25.7432	-80.062	90	N/A	N/A	2.91	0.25	0	0.253	2.2
Miami Central Inlet Deepwater Site (MCI)	15-Oct	e	e	e	25.7432	-80.062	120	N/A	N/A	8.25	0.09	0	0.636	4.65
Miami Central Inlet Deepwater Site (MCI)	15-Oct	f	f	f	25.7432	-80.062	150	0.026	0.049	10.88	0.04	0.64	1.444	6.52
Miami Central Outfall	16-Oct	10a	1	a	25.7427	-80.0859	0	0.461	0.128	2.23	1.58	66.32	3.552	8.07
Miami Central Outfall	16-Oct	2a	2	a	25.7436	-80.0856	0	0.416	0.096	0.53	0.31	5.37	0.402	1.2
Miami Central Outfall	16-Oct	3a	3	a	25.7435	-80.0858	0	0.428	0.097	1	0.61	10.97	0.704	2
Miami Central Outfall	16-Oct	4a	4	a	25.7435	-80.0859	0	0.429	0.099	1.26	0.8	15.94	0.995	2.62
Miami Central Outfall	16-Oct	5a	5	a	25.7443	-80.0858	0	0.422	0.105	0.66	0.41	11.42	0.573	1.73
Miami Central Outfall	16-Oct	6a	6	a	25.7443	-80.086	0	0.399	0.096	0.57	0.36	10.68	0.579	1.6
Miami Central Outfall	16-Oct	7a	7	a	25.7444	-80.0862	0	0.461	0.116	0.48	0.29	8.92	0.467	1.36
Miami Central Outfall	16-Oct	8a	8	a	25.7448	-80.0856	0	0.411	0.089	0.38	0.22	7.77	0.403	1.25
Miami Central Outfall	16-Oct	9a	9	a	25.7448	-80.0861	0	0.431	0.110	0.27	0.16	6.41	0.356	1.11
Miami Central Outfall	16-Oct	1a	10	a	25.7457	-80.0852	0	0.488	0.105	0.57	0.32	4.01	0.474	1.01
Miami Central Outfall	16-Oct	10b	1	b	25.7427	-80.0859	15.65	0.448	0.122	0.57	0.37	15.94	1.48	2.11
Miami Central Outfall	16-Oct	2b	2	b	25.7436	-80.0856	16.61	0.429	0.093	0.55	0.33	5.61	0.443	1.11
Miami Central Outfall	16-Oct	3b	3	b	25.7435	-80.0858	16.06	0.596	0.121	0.79	0.49	9.08	0.624	1.63
Miami Central Outfall	16-Oct	6b	6	b	25.7443	-80.086	15.37	0.434	0.094	0.28	0.15	4.64	0.235	0.87
Miami Central Outfall	16-Oct	7b	7	b	25.7444	-80.0862	14.49	0.451	0.095	0.13	0.05	1.79	0.134	0.41
Miami Central Outfall	16-Oct	8b	8	b	25.7448	-80.0856	16.26	0.397	0.091	0.01	0	0.11	0.111	0.17
Miami Central Outfall	16-Oct	9b	9	b	25.7448	-80.0861	14.72	0.386	0.107	0.14	0.07	3.19	0.255	0.66
Miami Central Outfall	16-Oct	1b	10	b	25.7457	-80.0852	17.15	0.475	0.110	0.05	0	0.35	0.112	0.25

Nancy Foster	Date	Site			Latitude	Longitude	Depth	Chlorophyll a	Phaeo	NO_3+NO_2 [N]	NO_2 [N]	NH_4-N	P	Si
Oct-06		surface	mid	bottom			(m)	(µg/L)	(µg/L)	(µM)	(µM)	(µM)	(µM)	(µM)
Miami Central Outfall	16-Oct	10c	1	c	25.7427	-80.0859	31.3	0.527	0.173	0.16	0.02	1.12	0.304	0.31
Miami Central Outfall	16-Oct	2c	2	c	25.7436	-80.0856	33.22	0.526	0.123	0.04	0	0.29	0.078	0.17
Miami Central Outfall	16-Oct	3c	3	c	25.7435	-80.0858	32.13	0.429	0.099	0.05	0	0.23	0.144	0.12
Miami Central Outfall	16-Oct	4c	4	c	25.7435	-80.0859	31.52	0.545	0.126	0.05	0	0.11	0	0.06
Miami Central Outfall	16-Oct	5c	5	c	25.7443	-80.0858	32.31	0.590	0.151	0.19	0.01	0.11	0.02	0.17
Miami Central Outfall	16-Oct	6c	6	c	25.7443	-80.086	30.75	0.550	0.133	0.08	0.01	0.16	0.12	0.14
Miami Central Outfall	16-Oct	7c	7	c	25.7444	-80.0862	28.99	0.447	0.104	0.07	0	0.24	0.011	0.17
Miami Central Outfall	16-Oct	8c	8	c	25.7448	-80.0856	32.52	0.662	0.206	0.13	0.02	0.16	0.076	0.25
Miami Central Outfall	16-Oct	9c	9	c	25.7448	-80.0861	29.44	0.523	0.138	0.12	0.01	0.32	0.098	0.2
Miami Central Outfall	16-Oct	1c	10	c	25.7457	-80.0852	34.3	0.578	0.128	0.07	0	0.58	0.118	0.17
Hollywood Outfall	17-Oct	10a	1	a	26.0197	-80.0856	0	0.333	0.046	0.77	0.46	3.17	0	1.32
Hollywood Outfall	17-Oct	1ab	2	a	26.0203	-80.0868	0	0.406	0.114	0.25	0.03	0.55	0.129	0.63
Hollywood Outfall	17-Oct	2a	3	a	26.0203	-80.0856	0	0.475	0.129	0.59	0.32	2.03	0.076	0.87
Hollywood Outfall	17-Oct	3a	4	a	26.0203	-80.0846	0	0.494	0.115	1.26	0.81	3.31	0.091	1.54
Hollywood Outfall	17-Oct	4a	5	a	26.0208	-80.0845	0	0.335	0.076	0.08	0	0	0	0.52
Hollywood Outfall	17-Oct	5a	6	a	26.0207	-80.0857	0	0.373	0.081	0.23	0.09	0.59	0	0.52
Hollywood Outfall	17-Oct	6a	7	a	26.0207	-80.0871	0	0.439	0.103	0.18	0.01	0	0	0.38
Hollywood Outfall	17-Oct	7a	8	a	26.0211	-80.0874	0	0.507	0.117	0.23	0.03	0	0	0.43
Hollywood Outfall	17-Oct	8a	9	a	26.0212	-80.0856	0	0.365	0.086	0.64	0.34	2.2	0	0.96
Hollywood Outfall	17-Oct	9a	10	a	26.0213	-80.084	0	0.177	0.058	0.03	0	0.15	0	0.35
Hollywood Outfall	17-Oct	10b	1	b	26.0197	-80.0856	14.25	0.244	0.064	0.16	0.01	0.54	0	0.4
Hollywood Outfall	17-Oct	1bb	2	b	26.0203	-80.0868	10.1	0.409	0.111	0.2	0.02	0.01	0.035	0.57
Hollywood Outfall	17-Oct	2b	3	b	26.0203	-80.0856	13.75	0.480	0.125	0.7	0.42	1.97	0.035	1.01
Hollywood Outfall	17-Oct	3b	4	b	26.0203	-80.0846	17.1	0.509	0.122	0.08	0	0	0	0.4
Hollywood Outfall	17-Oct	4b	5	b	26.0208	-80.0845	17.3	0.473	0.068	0.13	0	0.33	0	0.49
Hollywood Outfall	17-Oct	5b	6	b	26.0207	-80.0857	13.4	0.371	0.091	0.18	0.04	0.36	0	0.43
Hollywood Outfall	17-Oct	6b	7	b	26.0207	-80.0871	8	0.462	0.101	0.21	0.01	0	0	0.4
Hollywood Outfall	17-Oct	7b	8	b	26.0211	-80.0874	7.71	0.480	0.107	0.21	0.02	0.06	0	0.38
Hollywood Outfall	17-Oct	11	0	c	26.0186	-80.0861	25.24	0.214	0.065	5.95	4.56	30.22	0.83	8.26
Hollywood Outfall	17-Oct	10c	1	c	26.0197	-80.0856	28.5	0.384	0.096	0.12	0.01	0.23	0	0.4
Hollywood Outfall	17-Oct	1cb	2	c	26.0203	-80.0868	20.2	0.430	0.118	0.24	0.02	0.2	0	0.54
Hollywood Outfall	17-Oct	2c	3	c	26.0203	-80.0856	27.5	0.460	0.120	0.25	0	0.06	0	0.43
Hollywood Outfall	17-Oct	3c	4	c	26.0203	-80.0846	34.2	0.493	0.124	0.09	0	0	0	0.35

Nancy Foster	Date	Site			Latitude	Longitude	Depth	Chlorophyll a	Phaeo	NO_3+NO_2 [N]	NO_2 [N]	NH_4-N	P	Si
Oct-06		surface	mid	bottom			(m)	(µg/L)	(µg/L)	(µM)	(µM)	(µM)	(µM)	(µM)
Hollywood Outfall	17-Oct	4c	5	c	26.0208	-80.0845	34.6	0.483	0.108	0.19	0.02	0.1	0	0.43
Hollywood Outfall	17-Oct	5c	6	c	26.0207	-80.0857	26.8	0.397	0.095	0.26	0.02	0	0	0.38
Hollywood Outfall	17-Oct	6c	7	c	26.0207	-80.0871	16	0.453	0.098	0.19	0.01	0	0	0.38
Hollywood Outfall	17-Oct	7c	8	c	26.0211	-80.0874	15.42	0.550	0.094	0.18	0.02	0	0	0.32
Hollywood Outfall	17-Oct	8c	9	c	26.0212	-80.0856	27.5	0.394	0.096	0.15	0.01	0.07	0	0.49
Hollywood Outfall	17-Oct	9c	10	c	26.0213	-80.084	37.12	0.470	0.098	0.13	0.01	0.11	0	0.32
Miami North Outfall	17-Oct	1a	1	a	25.9192	-80.0863	0	0.778	0.200	29	1	12.85	0.78	3.24
Miami North Outfall	17-Oct	2a	2	a	25.9196	-80.0863	0	0.642	0.189	2.81	1.77	26.1	1.708	5.78
Miami North Outfall	18-Oct	3a	3	a	25.9217	-80.0848	0	0.402	0.124	0.37	0.23	2.66	0.13	0.9
Miami North Outfall	18-Oct	4a	4	a	25.9212	-80.0843	0	0.398	0.124	0.21	0.12	1.36	0.064	0.44
Miami North Outfall	18-Oct	5a	5	a	25.9207	-80.0844	0	0.412	0.120	0.58	0.39	5.08	2	1.14
Miami North Outfall	18-Oct	6a	6	a	25.921	-80.0868	0	0.560	0.112	0.76	0.5	6.02	0.421	1.63
Miami North Outfall	18-Oct	7a	7	a	25.9212	-80.0867	0	0.437	0.122	0.68	0.44	6.2	0	1.53
Miami North Outfall	18-Oct	8a	8	a	25.9217	-80.0868	0	0.417	0.128	0.13	0.01	0	0	0.1
Miami North Outfall	18-Oct	9a	9	a	25.9218	-80.0884	0	0.825	0.218	0.35	0.22	2.52	0	1.77
Miami North Outfall	18-Oct	10a	10	a	25.9213	-80.0883	0	0.874	0.265	0.08	0.04	0	0	1.24
Miami North Outfall	18-Oct	11a	11	a	25.9209	-80.0883	0	0.900	0.256	0.07	0.01	0	0	1.29
Miami North Outfall	17-Oct	1b	1	b	25.9192	-80.0863	15.33	0.517	0.188	1.708	0.49	4.79	0.243	1.71
Miami North Outfall	18-Oct	3b	3	b	25.9217	-80.0848	18.6	0.468	0.141	0.08	0.02	0	0	0.36
Miami North Outfall	18-Oct	4b	4	b	25.9212	-80.0843	19.02	0.390	0.112	0.06	0.01	0	0	0.17
Miami North Outfall	18-Oct	5b	5	b	25.9207	-80.0844	19.02	0.384	0.115	0.04	0.02	0	0	0.11
Miami North Outfall	18-Oct	6b	6	b	25.921	-80.0868	14.01	0.396	0.117	0.11	0.04	0	0.041	0.27
Miami North Outfall	18-Oct	7b	7	b	25.9212	-80.0867	14.8	0.530	0.136	0.1	0.03	0	0	0.13
Miami North Outfall	18-Oct	8b	8	b	25.9217	-80.0868	14.4	0.492	0.129	0.11	0.01	0	0	0.1
Miami North Outfall	18-Oct	9b	9	b	25.9218	-80.0884	10.18	0.687	0.177	0.34	0.2	3.12	0	1.34
Miami North Outfall	18-Oct	10b	10	b	25.9213	-80.0883	10.4	0.776	0.219	0.05	0.03	0	0	0.91
Miami North Outfall	18-Oct	11b	11	b	25.9209	-80.0883	13.6	0.594	0.169	0	0	0	0	0.02
Miami North Outfall	17-Oct	1c	1	c	25.9192	-80.0863	30.66	0.845	0.279	0.26	0.14	0.02	0.029	0.62
Miami North Outfall	18-Oct	5c	5	c	25.9207	-80.0844	38.04	0.414	0.122	0.11	0.03	0	0	0.11
Miami North Outfall	18-Oct	6c	6	c	25.921	-80.0868	28.2	0.430	0.119	0.3	0.04	0	0.061	0.25
Miami North Outfall	18-Oct	7c	7	c	25.9212	-80.0867	29.6	0.422	0.123	0.12	0.01	0	0	0.1
Miami North Outfall	18-Oct	8c	8	c	25.9217	-80.0868	28.8	0.433	0.139	0.19	0.02	0.12	0	0.21
Miami North Outfall	18-Oct	9c	9	c	25.9218	-80.0884	20.36	0.486	0.113	0.24	0.03	0	0	0.18

Nancy Foster	Date	Site			Latitude	Longitude	Depth	Chlorophyll a	Phaeo	NO_3+NO_2 [N]	NO_2 [N]	NH_4-N	P	Si
Oct-06		surface	mid	bottom			(m)	(µg/L)	(µg/L)	(µM)	(µM)	(µM)	(µM)	(µM)
Miami North Outfall	18-Oct	10c	10	c	25.9213	-80.0883	20.8	0.479	0.156	0.21	0.02	0	0	0.29
Miami North Outfall	18-Oct	11c	11	c	25.9209	-80.0883	27.2	0.523	0.149	0.14	0.02	0	0	0.05
South Central Outfall	12-Oct	1	1	a	26.4627	-80.042	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A
South Central Outfall	12-Oct	2a	2	a	26.4642	-80.0434	0	0.343	0.111	N/A	N/A	N/A	N/A	N/A
South Central Outfall	12-Oct	3a	3	a	26.4638	-80.0416	0	0.422	0.121	N/A	N/A	N/A	N/A	N/A
South Central Outfall	12-Oct	4a	4	a	26.4631	-80.0424	0	0.402	0.126	N/A	N/A	N/A	N/A	N/A
South Central Outfall	12-Oct	5a	5	a	26.463	-80.0431	0	0.398	0.126	N/A	N/A	N/A	N/A	N/A
South Central Outfall	12-Oct	6a	6	a	26.4631	-80.0417	0	0.403	0.115	N/A	N/A	N/A	N/A	N/A
South Central Outfall	12-Oct	7a	7	a	26.4636	-80.0424	0	0.362	0.094	N/A	N/A	N/A	N/A	N/A
South Central Outfall	12-Oct	8a	8	a	26.4637	-80.0411	0	0.439	0.119	N/A	N/A	N/A	N/A	N/A
South Central Outfall	12-Oct	9a	9	a	26.4642	-80.0427	0	0.422	0.134	N/A	N/A	N/A	N/A	N/A
South Central Outfall	12-Oct	10a	10	a	26.4642	-80.0442	0	0.455	0.129	N/A	N/A	N/A	N/A	N/A
South Central Outfall	12-Oct	11a	11	a	26.4623	-80.042	0	0.279	0.084	N/A	N/A	N/A	N/A	N/A
South Central Outfall	12-Oct	1b	1	b	26.4623	-80.042	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A
South Central Outfall	12-Oct	2b	2	b	26.4642	-80.0434	10.56	0.424	0.104	N/A	N/A	N/A	N/A	N/A
South Central Outfall	12-Oct	3b	3	b	26.4638	-80.0416	15.19	0.518	0.204	N/A	N/A	N/A	N/A	N/A
South Central Outfall	12-Oct	4b	4	b	26.4631	-80.0424	13.56	0.434	0.137	N/A	N/A	N/A	N/A	N/A
South Central Outfall	12-Oct	5b	5	b	26.463	-80.0431	12	0.406	0.132	N/A	N/A	N/A	N/A	N/A
South Central Outfall	12-Oct	6b	6	b	26.4631	-80.0417	15.01	0.407	0.128	N/A	N/A	N/A	N/A	N/A
South Central Outfall	12-Oct	7b	7	b	26.4636	-80.0424	13.8	0.437	0.122	N/A	N/A	N/A	N/A	N/A
South Central Outfall	12-Oct	8b	8	b	26.4637	-80.0411	15.82	0.231	0.075	N/A	N/A	N/A	N/A	N/A
South Central Outfall	12-Oct	9b	9	b	26.4642	-80.0427	11.51	0.418	0.129	N/A	N/A	N/A	N/A	N/A
South Central Outfall	12-Oct	10b	10	b	26.4642	-80.0442	9.84	0.533	0.145	N/A	N/A	N/A	N/A	N/A
South Central Outfall	12-Oct	11b	11	b	26.4623	-80.042	14.69	0.214	0.074	N/A	N/A	N/A	N/A	N/A
South Central Outfall	12-Oct	2c	2	c	26.4642	-80.0434	21.12	0.316	0.144	N/A	N/A	N/A	N/A	N/A
South Central Outfall	12-Oct	3c	3	c	26.4638	-80.0416	30.39	0.433	0.170	N/A	N/A	N/A	N/A	N/A
South Central Outfall	12-Oct	4c	4	c	26.4631	-80.0424	27.13	0.419	0.148	N/A	N/A	N/A	N/A	N/A
South Central Outfall	12-Oct	5c	5	c	26.463	-80.0431	24	0.429	0.138	N/A	N/A	N/A	N/A	N/A
South Central Outfall	12-Oct	8c	8	c	26.4637	-80.0411	31.64	0.481	0.196	N/A	N/A	N/A	N/A	N/A
South Central Outfall	12-Oct	9c	9	c	26.4642	-80.0427	23.02	0.412	0.139	N/A	N/A	N/A	N/A	N/A
South Central Outfall	12-Oct	10c	10	c	26.4642	-80.0442	19.69	0.486	0.135	N/A	N/A	N/A	N/A	N/A
South Central Outfall	12-Oct	11c	11	c	26.4623	-80.042	29.38	0.517	0.179	N/A	N/A	N/A	N/A	N/A
Boynton Inlet (BI)	12-Oct	1a	1	a	26.5445	-80.0375	0	0.844	0.371	N/A	N/A	N/A	N/A	N/A

Nancy Foster	Date	Site			Latitude	Longitude	Depth	Chlorophyll a	Phaeo	NO_3+NO_2 [N]	NO_2 [N]	NH_4-N	P	Si
Oct-06		surface	mid	bottom			(m)	(µg/L)	(µg/L)	(µM)	(µM)	(µM)	(µM)	(µM)
Boynton Inlet (BI)	12-Oct	1b	1	b	26.5445	-80.0375	8	0.855	0.377	N/A	N/A	N/A	N/A	N/A
C1, C2, C3	14-Oct	1a	1	a	26.2002	-80.0715	0	1.568	1.158	0.1	0.06	0	0	0
C1, C2, C3	14-Oct	1b	1	b	26.2002	-80.0715	9.35	1.704	1.471	0.13	0.08	0	0	0
C1, C2, C3	14-Oct	1c	1	c	26.2002	-80.0715	18.7	1.427	0.594	0.15	0.04	0	0	0
C1, C2, C3	14-Oct	2a	2	a	26.13	-80.082	0	1.657	0.519	0.14	0.05	0	0	0
C1, C2, C3	14-Oct	2b	2	b	26.13	-80.082	11.28	1.537	0.636	0.12	0.04	0	0	0
C1, C2, C3	14-Oct	2c	2	c	26.13	-80.082	22.56	1.192	0.361	0.23	0.05	0	0	0
C1, C2, C3	14-Oct	3a	3	a	26.0639	-80.0906	0	1.403	0.563	0.08	0.04	0	0	0
C1, C2, C3	14-Oct	3b	3	b	26.0639	-80.0906	11.25	1.166	0.569	0.24	0.05	0	0	0.06
C1, C2, C3	14-Oct	3c	3	c	26.0639	-80.0906	22.5	0.849	0.225	0.22	0.04	0	0	0.09