WATER QUALITY PROTECTION PROGRAM

FLORIDA KEYS NATIONAL MARINE SANCTUARY

WATER QUALITY MONITORING PROJECT
FY2000 ANNUAL REPORT

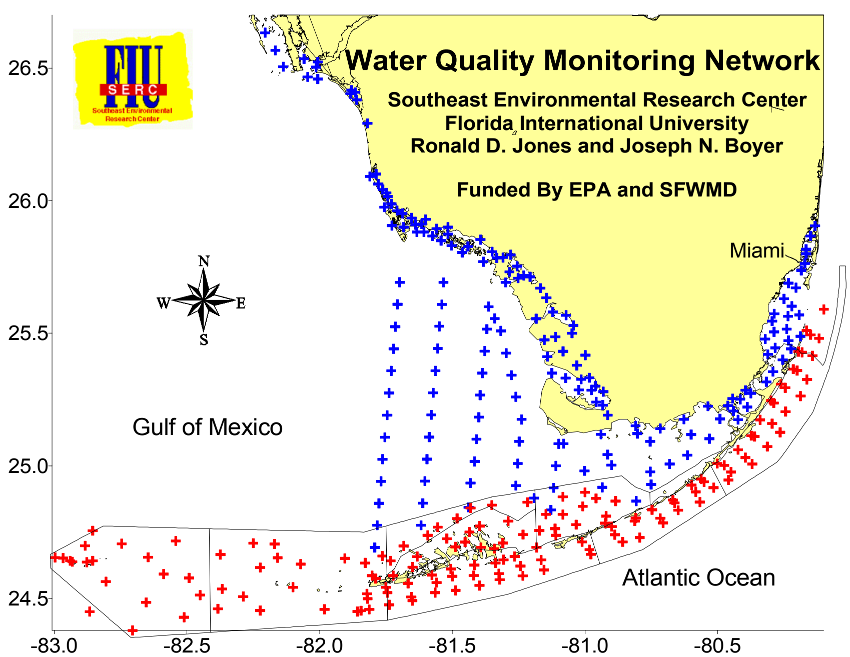

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Table of Contents

I. Executive Summary

This report serves as a summary of our efforts to date in the execution of the Water Quality Monitoring Project for the FKNMS as part of the Water Quality Protection Program. Since initiation we have added 4 sampling sites and adjusted 6 others to increase cover in the Sanctuary Preservation Areas and Ecological Reserves. We have received 28 requests for data by outside researchers working in the FKNMS of which one has resulted in a master's thesis. Two scientific manuscripts have been submitted for publication: one is a book chapter in The Everglades, Florida Bay, and the Coral Reefs of the Florida Keys: an Ecological Sourcebook. CRC Press.; the other is in special issue of Estuarine, Coastal and Shelf Science on visualization in coastal marine science. Two other manuscripts are being prepared; one in conjunction with the FKNMS seagrass monitoring program. We maintain a website where data from the FKNMS is integrated with the other parts of the SERC water quality network (Florida Bay, Whitewater Bay, Biscayne Bay, Ten Thousand Islands, and SW Florida Shelf) and displayed as downloadable contour maps - http://serc.fiu.edu/wqmnetwork/.

The period of record for this report is Mar. 1995 - July. 2000 and includes data from 21 quarterly sampling events at 154 stations within the FKNMS including the Dry Tortugas National Park. Field parameters at each station include salinity, temperature, dissolved oxygen (DO), turbidity, relative fluorescence, and light attenuation (K_d). Water chemistry variables measured at each station include the dissolved nutrients nitrate (NO_3^-), nitrite (NO_2^-), ammonium (NH_4^+), dissolved inorganic nitrogen (DIN), and soluble reactive phosphate (SRP). Total unfiltered concentrations of organic nitrogen (TON), organic carbon (TOC), phosphorus (TP), and silicate ($Si(OH)_4$) were also measured. The monitored biological parameters included chlorophyll *a* (CHLA) and alkaline phosphatase activity (APA).

Grouping stations by depth showed that temperature, DO, TOC, and TON were generally higher at the surface while salinity, NO_3^-, NO_2^-, NH_4^+, TP, and turbidity were higher in bottom waters. This slight stratification is indicative of a weak pycnocline which is maintained by freshwater inputs and solar heating at the surface. Elevated nutrients in the bottom waters is due to benthic flux and some upwelling. Stations grouped by to geographical region showed that the Tortugas and the Upper Keys had lower nutrient concentrations than the Middle Keys or Lower Keys. In the Lower Keys DIN was elevated in the Backcountry. TP concentrations in the Lower

Keys transects decreased with distance offshore but increased along transects in the Upper Keys, mostly because of low concentrations alongshore. The Sluiceway had lowest salinity and highest TOC, TON, and $Si(OH)_4$ concentrations. The north Marquesas area exhibited highest phytoplankton biomass for any segment of the FKNMS. Declining inshore to offshore trends were observed for NO_3^-, NH_4^+, $Si(OH)_4$, TOC, TON, and turbidity for all oceanside transects. Stations grouped by shore type showed that those stations situated along channels/passes possessed higher nutrient concentrations, phytoplankton biomass, and turbidity than those stations off land. These differences were very small but it is not known if they are biologically important. However, the fact that the benthic communities are different between these two habitats indicates that there may be some long term effects.

An Objective Classification Analysis was performed in an effort to group stations in the FKNMS according to water quality. This involved a multivariate statistical approach using principal components analysis followed by k-mean clustering analysis. The result was the deconvolution of 150 stations into 7 clusters possessing distinct water quality from each other (Fig. 18). We believe this is a more functional zonation of the FKNMS as it is driven by similarities in water quality.

Probably the most interesting result of our data analysis was the elucidation of temporal trends in TP, NO_3^-, and TON for much of the FKNMS. Trend analysis showed statistically significant increases in TP for the Tortugas, Marquesas, Lower Keys, and portions of the Middle and Upper Keys. These trends were remarkably linear and show little seasonality. The increases in TP were system wide and occurred outside the FKNMS on the SW Shelf as well. Rates of increase ranged from 0.01-0.07 $\mu M\ yr^{-1}$ which was significant considering initial concentrations to be ~0.1-0.2 μM. No trends in TP were observed in Florida Bay or in those FKNMS sites most influenced by transport of Florida Bay waters. The effect of increased TP on the phytoplankton biomass has not been shown to be significant; i.e. no concurrent increases in CHLA were observed.

Trends in NO_3^- seemed to be more seasonally driven. Rates of increase ranged from 0.04-0.18 $\mu M\ yr^{-1}$. These are large increases in NO_3^- concentrations; in many cases NO_3^- went from <0.05 to >1 μM. Most of the increases occurred in the Shelf, Tortugas, Marquesas, Lower Keys, and Upper Keys (Fig. 23).

Contrary to increases in TP and NO_3^-, TON declined at many sites over the period of record (Fig. 24). Decreases ranged from -0.7 to –2.7 μM yr^{-1} and were more modest as compared to ambient TON concentrations. Most of the decreases occurred in the Shelf, Sluiceway, Lower Keys, and Upper Keys (Fig. 25). It is possible that loss of TON was due to biological conversion to NO_3^-, but there was no significant correspondence between TON declines and NO_3^- increases. At this time we can only speculate as to the cause of these trends but believe them to be driven by regional circulation patterns arising from the Loop and Florida Currents.

The large scale of this monitoring program has allowed us to assemble a much more holistic view of broad physical/chemical/biological interactions occurring over the South Florida hydroscape. Much information has been gained by inference from this type of data collection program: major nutrient sources have be confirmed, relative differences in geographical determinants of water quality have been demonstrated, and large scale transport via circulation pathways have been elucidated. In addition we have shown the importance of looking "outside the box" for questions asked within. Rather than thinking of water quality monitoring as being a static, non-scientific pursuit it should be viewed as a tool for answering management questions and developing new scientific hypotheses. One of the more important management questions to be answered is "Is the water quality better or worse than it used to be?" This monitoring program based on quarterly sample intervals has revealed significant trends in TP, NO_3^-, and TON. We expect to see more trends in other variables as the database grows and we begin to tease out effects of seasonal variability.

II. Project Background

The Florida Keys are a archipelago of sub-tropical islands of Pleistocene origin which extend in a NE to SW direction from Miami to Key West and out to the Dry Tortugas (Fig. 1). In 1990, President Bush signed into law the Florida Keys National Sanctuary and Protection Act (HR5909) which designated a boundary encompassing >2,800 square nautical miles of islands, coastal waters, and coral reef tract as the Florida Keys National Marine Sanctuary (FKNMS). The Comprehensive Management Plan (NOAA 1995) required the FKNMS to have a Water Quality Protection Plan (WQPP) thereafter developed by EPA and the State of Florida (EPA 1995). The contract for the water quality monitoring component of the WQPP was subsequently awarded to the Southeast Environmental Research Program at Florida International University and the field sampling program began in March 1995.

The waters of the FKNMS are characterized by complex water circulation patterns over both spatial and temporal scales with much of this variability due to seasonal influence in regional circulation regimes. The FKNMS is directly influenced by the Florida Current, the Gulf of Mexico Loop Current, inshore currents of the SW Florida Shelf (Shelf), discharge from the Everglades through the Shark River Slough, and by tidal exchange with both Florida Bay and Biscayne Bay (Lee et al. 1994). Advection from these external sources has significant effects on the physical, chemical, and biological composition of waters within the FKNMS, as may internal nutrient loading and freshwater runoff from the Keys themselves. Water quality of the FKNMS may be directly affected both by external nutrient transport and internal nutrient loading sources. Therefore, the geographical extent of the FKNMS is one of political/regulatory definition and should not be thought of as an enclosed ecosystem.

A spatial framework for FKNMS water quality management was proposed on the basis of geographical variation of regional circulation patterns (Klein and Orlando, 1994). The final implementation plan (EPA, 1995) partitioned the FKNMS into 9 segments which was collapsed to 7 for routine sampling (Fig. 1). Station locations were developed using a stratified random design along onshore/offshore transects in Segment 5, 7, and 9 or within EMAP grid cells in Segment 1, 2, 4, and 6.

Segment 1 (Tortugas) includes the Dry Tortugas National Park (DTNP) and surrounding waters and is most influenced by the Loop Current and Dry Tortugas Gyre. Originally, there were no sampling sites located within the DTNP as it was outside the jurisdiction of NOAA. Upon request from the National Park Service, we initiated sampling at 5 sites within the DNTP boundary. Segment 2 (Marquesas) includes the Marquesas Keys and a shallow sandy area between the Marquesas and Tortugas called the Quicksands. Segment 4 (Backcountry) contains the shallow, hard-bottomed waters on the gulfside of the Lower Keys. Segments 2 and 4 are both influenced by water moving south along the SW Shelf. Segment 6 can be considered as part of western Florida Bay. This area is referred to as the Sluiceway as it strongly influenced by transport from Florida Bay, SW Shelf, and Shark River Slough (Smith, 1994). Segments 5 (Lower Keys), 7 (Middle Keys), and 9 (Upper Keys) include the inshore, Hawk Channel, and reef tract of the Atlantic side of the Florida Keys. The Lower Keys are most influenced by cyclonic gyres spun off of the Florida Current, the Middle Keys by exchange with Florida Bay, while the Upper Keys are influenced by the Florida Current frontal eddies and to a certain extent by exchange with Biscayne Bay. All three oceanside segments are also influenced by wind and tidally driven lateral Hawk Channel transport (Pitts, 1997).

We have found that water quality monitoring programs composed of many sampling stations situated across a diverse hydroscape are often difficult to interpret due to the "not able see the forest for the trees" problem (Boyer et al. 2000). At each site, the many measured variables are independently analyzed, individually graphed, and separately summarized in tables. This approach makes it difficult to see the larger, regional picture or to determine any associations among sites. In order to gain a better understanding of the spatial patterns of water quality of the FKNMS, we attempted to reduce the complicated data matrix into fewer elements which would provide robust estimates of condition and connection. To this end we developed an objective classification analysis procedure which grouped stations according to water quality similarity.

Ongoing quarterly sampling of >200 stations in the FKNMS and Shelf, as well as monthly sampling of 100 stations in Florida Bay, Biscayne Bay, and the mangrove estuaries of the SW coast, has provided us with a unique opportunity to explore the spatial component of water quality variability. By stratifying the sampling stations according to depth, regional geography, distance from shore, proximity to tidal passes, and influence of Shelf waters we report some preliminary conclusions as to the relative importance of external vs. internal factors on the ambient water quality within the FKNMS.

III. Methods

Field Sampling

The period of record of this study was from March 1995 to July 2000 which included 21 quarterly sampling events. For each event, field measurements and grab samples were collected from 150 fixed stations within the FKNMS boundary (Fig. 2). Depth profiles of temperature (°C), salinity (practical salinity scale), dissolved oxygen (DO, mg l^{-1}), photosynthetically active radiation (PAR, $\mu E\ m^{-2}\ s^{-1}$), in situ chlorophyll *a* specific fluorescence (FSU), optical backscatterance turbidity (OBS), depth as measured by pressure transducer (m), and density (σ_t, in kg m^{-3}) were measured by CTD casts (Seabird SBE 19). The CTD was equipped with internal RAM and operated in stand alone mode at a sampling rate of 0.5 sec. To determine the extent of stratification we calculated the difference between surface and bottom density as delta sigma-t ($\Delta\sigma_t$), where positive values denoted greater density of bottom water relative to the surface. The vertical light attenuation coefficient (K_d, m^{-1}) was calculated at 0.5 m intervals from PAR and depth using the standard exponential equation (Kirk 1994) and averaged over the station depth. This was necessary due to periodic occurrence of optically distinct layers within the water column. During these events, K_d was reported for the upper layer.

In the Backcountry area (Seg. 4, Fig. 1) where it was too shallow to use a CTD, surface salinity and temperature were measured using a combination salinity-conductivity-temperature probe (Orion model 140). DO was measured using an oxygen electrode (Orion model 840) corrected for salinity and temperature. PAR was measured using a Li-Cor irradiance meter equipped with two 4π spherical sensors (LI-193SB) separated by 0.5 m in depth and oriented at 90° to each other. The light meter measured instantaneous difference between sensors which was then used to calculate K_d from in-air surface irradiance.

Water was collected from approximately 0.25 m below the surface and at approximately 1 m from the bottom with a teflon-lined Niskin bottle (General Oceanics) except in the Backcountry where it was collected directly into sample bottles. Duplicate, unfiltered water samples were collected using 3x sample rinsed 120 ml HDPE bottles for analysis of total constituents. Duplicate water samples for dissolved nutrients were collected using 3x sample rinsed 150 ml syringes which were then filtered by hand through 25 mm glass fiber filters (Whatman GF/F) into 3x sample rinsed 60 ml HDPE bottles. The wet filters, used for chlorophyll *a* (CHLA) analysis, were placed in 1.8 ml plastic centrifuge tubes to which 1.5 ml of 90 % acetone/water was added (Strickland and Parsons 1972).

Unfiltered samples were kept at ambient temperature in the dark during transport to the laboratory. During shipboard collection in the Tortugas/Marquesas and overnight stays in the Keys, unfiltered samples were analyzed for APA and turbidity prior to refrigeration. Filtered samples and CHLA filters were kept on ice in the dark during transport. During shipboard collection in the Tortugas/Marquesas and overnight stays in the lower Keys, filtrates and filters were frozen until analysis.

Laboratory Analysis

Unfiltered water samples were analyzed for total organic carbon (TOC), total nitrogen (TN), total phosphorus (TP), silicate ($Si(OH)_4$), alkaline phosphatase activity (APA), and turbidity. TOC was measured by direct injection onto hot platinum catalyst in a Shimadzu TOC-5000 after first acidifying to pH<2 and purging with CO_2-free air. TN was measured using an ANTEK 7000N Nitrogen Analyzer using O_2 as carrier gas to promote complete recovery of the nitrogen in the water samples (Frankovich and Jones 1998). TP was determined using a dry ashing, acid hydrolysis technique (Solórzano and Sharp 1980). $Si(OH)_4$ was measured using the molybdosilicate method (Strickland and Parsons 1972). The APA assay measures the activity of alkaline phosphatase, an enzyme used by bacteria and algae to mineralize orthophosphate from organic compounds. The assay is performed by adding a known concentration of methylfluorescein phosphate to an unfiltered water sample. Alkaline phosphatase in the water sample cleaves the orthophosphate, leaving methylfluorescein, a highly fluorescent compound. Fluorescence at initial and after 2 hr incubation were measured using a Gilford Fluoro IV Spectrofluorometer (excitation = 430 nm, emission = 507 nm) and subtracted to give APA in µM

h^{-1} (Jones 1996). Turbidity was measured using an HF Scientific model DRT-15C turbidimeter and reported in NTU.

Filtrates were analyzed for soluble reactive phosphorus (SRP), nitrate+nitrite (NO_x^-), nitrite (NO_2^-), and total ammonia (NH_4^+) by flow injection analysis (Alpkem model RFA 300). Filters for CHLA content ($\mu g\ l^{-1}$) were allowed to extract for a minimum of 2 days at -20°C before analysis. Extracts were analyzed using a Gilford Fluoro IV Spectrofluorometer (excitation = 435 nm, emission = 667 nm). All analyses were completed within 1 month after collection in accordance to SERC laboratory quality control guidelines.

Some parameters were not measured directly, but were calculated by difference. Nitrate (NO_3^-) was calculated as $NO_X^- - NO_2^-$, dissolved inorganic nitrogen (DIN) as $NO_X^- + NH_4^+$, and total organic nitrogen (TON) defined as TN - DIN. All concentrations are reported as µM unless noted. All elemental ratios discussed were calculated on a molar basis. DO saturation in the water column (DO_{sat} as %) was calculated using the equations of Garcia and Gordon (1992).

Spatial Stratification

Stations were stratified five different ways for statistical analysis: by depth (surface or bottom), by Segment, by distance along transect, by shore type, and by objective classification analysis. The first four station groupings were subjectively defined using best available knowledge in an effort to provide information as to source, transport, and fate of water quality components. For the first grouping, stations were selected as those >3 m depth where both surface and bottom samples were collected. The second grouping included surface samples stratified by Segment (Fig. 1) in accordance with the implementation plan (EPA, 1995). The third category consisted of those stations situated on ocean-side transects aggregated according to their distance from shore as: Alongshore, Hawk Channel, or Reef Tract. We initiated a similar transect of stations in the Tortugas off Loggerhead Key to serve as a reference.

One of the concerns of this program was to determine the contribution of water movement through the passes of the Keys to the water quality on the reef tract. To this end we decided to characterize the fourth grouping of transects by shore type: those that were adjacent to land off shore of Biscayne National Park including Old Rhodes Key, Elliot Key and the Safety Valve

(BISC), those that abutted land in Key Largo, Middle, and Lower Keys (LAND), and those transects which were aligned along the open channels or passes through the Keys (PASS).

Finally, we thought it important to objectively group stations according to water quality characteristics (i.e. physical, chemical, and biological variables) using a more objective, statistical approach. Multivariate statistical techniques have been shown to be useful in reducing a large data sets into a smaller set of independent, synthetic variables that capture much of the original variance. One method is to perform an objective classification analysis (OCA) by using principal component analysis (PCA) followed by k-means clustering algorithm to classify sites as to their overall water quality. This approach has be used to aid in understanding the factors influencing nutrient biogeochemistry in Florida Bay (Boyer et al., 1997) and Ten Thousand Islands (Boyer and Jones, 1998). We have found that water quality at a specific site is the result of the interaction of a variety of driving forces including oceanic and freshwater inputs/outputs, sinks, and internal cycling. The utility of this approach for further analysis and new hypothesis development will be discussed.

These subjective grouping strategies are presented as examples of how we assessed spatial differences in water quality during the initial phase of data collection. As mentioned in previous reports, subjective grouping strategies were to be dropped when enough data was collected (~5-7 yr) to be analyzed using a statistically objective, multivariate approach. However, we found that the ultimate users of the data interpretations: managers, scientists, and public prefer to think of the Sanctuary in terms of Segments and transect distances so we will continue to provide data analyses using these subjective stratifications.

Objective Classification Analysis

In order to assess the underlying patterns in the distribution of the measured parameters of the FKNMS, we followed the OCA procedure of Boyer et al. (1997). Briefly, data were first standardized as Z-scores prior to analysis to reduce artifacts of differences in magnitude among variables. PCA was then used to extract statistically significant composite variables (principal components) from the original data (Overland and Preisendorfer 1982). The PCA solution was rotated (using VARIMAX) in order to facilitate the interpretation of the principal components and the factor scores were saved for each data record. Both the mean and SD of the factor scores for each station over the period of record were then used as independent variables in a cluster analysis (k-means algorithm) in order to aggregate stations into groups of similar water quality. The purpose of this analysis was to collapse the 150 stations into a few groups which could then be analyzed in more detail.

Box and Whisker Plots

Typically, water quality variables are skewed to the left resulting in non-normal distributions; therefore it is more appropriate to use the median as the measure of central tendency (Christian et al. 1991). Data distributions of selected water quality variables are reported as box-and-whiskers plots. The box-and-whisker plot is a powerful statistic as it shows the median, range, the data distribution as well as serving as a graphical, nonparametric ANOVA. The center horizontal line of the box is the median of the data, the top and bottom of the box are the 25th and 75th percentiles (quartiles), and the ends of the whiskers are the 5th and 95th percentiles. The notch in the box is the 95% confidence interval of the median. When notches between boxes do not overlap, the medians are considered significantly different. Outliers (<5th and >95th percentiles) were excluded from the graphs to reduce visual compression. Differences in variables were also tested between groups using the Wilcoxon Ranked Sign test (comparable to *t*-test) and among groups by the Kruskall-Wallace test (ANOVA) with significance set at $P<0.05$.

Contour Maps

In an effort to elucidate the contribution of external factors to the water quality of the FKNMS and to visualize gradients in water quality over the region, we combined data from other portions of our water quality monitoring network: Florida Bay, Biscayne Bay, Whitewater Bay, Ten Thousand Islands, SW Shelf, and Marco Island – Ft. Meyers (Fig. 2 and see Appendix 1). Data from these 153 additional stations was collected during the same month as the FKNMS surveys and analyzed by the SERC laboratory using similar methodology and quality control as previously described. Contour maps were produced using Surfer (Golden Software). The most important aspect of generating contour maps is the geostatistical algorithm used for interpolating the data values. Care should be taken in the selection of the algorithm because automated interpolation to a regular rectangular grid can produce artifacts, especially around the edges and when the area of interest is irregularly shaped. Kriging was used because it is designed to minimize the error variance while at the same time maintaining point pattern continuity (Isaaks & Srivastava, 1989). Kriging is a global approach which uses standard geostatistics to determine the "distance" of influence around each point and the "clustering" of similar samples sites (autocorrelation). Therefore, unlike the inverse distance procedure, kriging will not produce valleys in the contour between neighboring points of similar value.

Time Series Analysis

Individual site data for the complete period of record were plotted as time series graphs (see separate Data Appendix) to illustrate any temporal trends that might have occurred. Temporal trends were quantified by simple regression with significance set at $P<0.10$. We originally wanted to use a seasonal Kendall-τ analysis to test for monotonic trend (Hirsch et al. 1991) but found that it was not applicable to the short, quarterly sampled data set.

IV. Results and Discussion

Overall Water Quality

Summary statistics for all water quality variables from all 21 sampling events are shown as median, minimum, maximum, and number of samples (Table 1). Overall, the region was warm and euhaline with a median temperature of 27.4°C and salinity of 36.2; oxygen saturation of the water column (DO_{sat}) was relatively high at 91%. On this coarse scale, the FKNMS exhibited very good water quality with median NO_3^-, NH_4^+, and TP concentrations of 0.098, 0.337, and 0.194 µM, respectively. NH_4^+ was the dominant DIN species in almost all of the samples (~70 %). DIN comprised a small fraction (4 %) of the TN pool with TON making up the bulk (median 10.30 µM). SRP concentrations were very low (median 0.010 µM) and comprised only 6 % of the TP pool. CHLA concentrations were also very low overall, 0.28 µg l^{-1}, but ranged from 0.01 to 15.2 µg l^{-1}. TOC was 207.8; higher than open ocean levels but consistent with coastal inputs. Median turbidity was low (0.6 NTU) as reflected in a low K_d (0.229 m^{-1}). This resulted in a median photic depth (to 1 % incident PAR) of ~22 m. Molar ratios of N to P suggested a general P limitation of the water column; median TN:TP = 59 and median DIN:SRP = 36.

Stations Grouped by Depth

Some differences were observed for those stations >3 m depth where both surface and bottom nutrient concentrations were measured (not shown). Overall, salinity, temperature, DO_{sat}, TON, TOC, and $Si(OH)_4$ were significantly higher at the surface while NO_3^-, NO_2^-, NH_4^+, and turbidity were significantly higher in bottom waters. There were no significant differences in TP, SRP, or APA with depth. Solar heating caused the increase in temperature and salinity of surface waters. Terrestrial freshwater inputs of TOC, TON, and $Si(OH)_4$ were responsible for higher concentrations in surface waters. Higher concentrations of DIN in bottom waters was most probably due to benthic flux or upwelling, while increased turbidity was due to bottom currents and sediment proximity.

Stations Grouped By Segment

NO_3^- was highest in the Backcountry (0.18 µM) followed by the Lower and Middle Keys (Fig. 4). Interestingly, NO_3^- concentrations in the Sluiceway (0.08 µM) were not significantly different than the Upper Keys, Tortugas, or Marquesas. Median NO_2^- concentrations in the Tortugas and Marquesas (0.03 µM) were significantly lower than for the other Keys segments (not shown). NH_4^+ was highest in the Backcountry (0.46 µM) and lowest in the Tortugas, Marquesas, and Upper Keys (~0.25 µM). The Middle Keys were significantly higher in NH_4^+ of any of the ocean-side segments.

TP was highest in the Backcountry and Sluiceway (~0.22 µM) and lowest in the Upper Keys (0.15 µM) with the remaining segments being intermediate (Fig. 2). TP was higher in the Tortugas and Marquesas because of the influence of the Gulf of Mexico waters. Lowest TP occurred off the Upper Keys. SRP was very low (~0.01 µM) for all areas but was slightly elevated and most variable in the Marquesas and Backcountry. Median $Si(OH)_4$ concentrations were highest in the Sluiceway (5.9 µM), lowest in the Tortugas, Marquesas, and Upper Keys (~0.45 µM), and intermediate in the Backcountry, Lower, and Middle Keys (~1.4 µM). Consistently higher CHLA concentrations were observed in the Marquesas (0.41 µg l^{-1}) than for any other area of the FKNMS. Lowest CHLA concentrations were found off the Upper Keys (0.20 μg l^{-1}).

The organic C and N pools as well as APA showed remarkable similarity in relative concentration among segments (Fig. 5). Highest median TOC (~260 μM), TON (~15.5 μM), and APA (~0.08 μM h^{-1}) were observed in the Backcountry and Sluiceway which declined SW towards the Tortugas and NE towards the Upper Keys. Median DO_{sat} was relatively similar among segments but was significantly higher and more variable in the Backcountry and Sluiceway (~95 %). This result would not have been evident had we only reported DO in mg l^{-1} as it was not significant across segments.

Salinity was comparable for most segments but was slightly lower in the Sluiceway (Fig. 5). Salinity in the Sluiceway and Backcountry were highly variable and precluded any statistical discrimination from the other segments. Turbidity was highest in the Backcountry (1.0 NTU), Sluiceway (0.85 NTU), and Marquesas (0.83 NTU) with lowest turbidity occurring in the Tortugas segment (0.35 NTU, Fig. 5). The shallow Quicksands area in the Marquesas probably accounted for the elevated turbidity in this segment. The Middle Keys showed high variability in turbidity although the overall median was low.

The Sluiceway and Marquesas had significantly higher water temperature (~28.1°C) than the other segments (Fig. 6). Of the ocean transects, the Lower Keys had higher water temperatures than the other Segments. Light attenuation showed a similar pattern as turbidity with highest K_d in Sluiceway (0.36 m^{-1}) and Backcountry stations (0.31 m^{-1}) and lowest K_d in the Tortugas (0.12 m^{-1}). This works out to respective median photic depths of 13, 15, and 38 m. Median TN:TP ratios in the Tortugas (45) and Marquesas (42) were significantly lower than in the other segments (Fig. 6). Much of this difference was due to decreased TON concentrations in these areas rather than higher TP. Lowest DIN:SRP ratios were found in the Marquesas (29) followed by the Tortugas (39). Decreased DIN as well as elevated SRP in the Marquesas relative to the Tortugas was responsible for these differences.

Stations Grouped By Distance along Transect

Median concentrations of NO_3^- in the Middle, and Lower Keys were significantly higher in Alongshore stations than those of Hawk Channel and Reef Tract (Fig. 7). Alongshore NO_3^- in the Upper Keys and Tortugas (~0.1 µM) was not nearly as high as found in the Middle and Lower Keys (~2.5 µM). NO_3^-concentrations on the Reef Tract and offshore in the Tortugas, Upper, and Middle Keys were comparable (~0.05 µM) and were all significantly lower than for the Lower Keys. NH_4^+ concentrations followed similar trends as NO_3^- being higher in Alongshore stations in the Middle and Lower Keys declining with distance offshore (Fig. 7). Alongshore NH_4^+ was highest in the Middle Keys (~0.5 µM). No significant differences in NH_4^+ was seen among Hawk Channel, Reef Tract, and Tortugas groups (~0.3 µM).

Alongshore sites TP concentrations (~0.18 µM) were significantly higher than the Reef Tract in the Middle and Lower Keys (Fig. 7). The Tortugas showed no offshore trend while the Upper Keys showed a slight increasing trend in TP from shore to reef. TP concentrations in the Upper, Middle, and Lower Keys were comparable (~0.18 µM) while the Tortugas were lowest overall (~0.16 µM). The major trends in TP were mirrored by SRP but were not statistically significant. Median $Si(OH)_4$ concentrations dropped dramatically with distance offshore in the Middle Keys (Fig. 7). In the Lower Keys, $Si(OH)_4$ was significantly lower only in the Reef Tract stations. There was no difference in $Si(OH)_4$ concentrations in the Upper Keys or Tortugas transects. Alongshore $Si(OH)_4$ concentrations were highest in the Middle Keys (~3 µM) while Reef Tract concentrations were highest in the Lower Keys (~0.5 µM).

There was no significant trend in CHLA with distance from land in the Lower Keys (Fig. 8), although there was a slight decline in the Middle Keys and a small increase in the Upper Keys. CHLA in the Offshore Tortugas sites was significantly lower than Alongshore and Channel sites but was comparable to levels in the Upper Keys (0.2 µg l^{-1}). TOC in the Lower, Middle, and Upper Keys was elevated Alongshore and declined sequentially through Hawk Channel to the Reef Tract (Fig. 8). There was no significant difference in TOC within Tortugas groups (~170 µM) and was similar to Reef Tract concentrations in the Keys. Highest TOC in Alongshore stations occurred in the Middle Keys (~250 µM). TON concentrations exhibited similar patterns as TOC (data not shown).

Turbidity in all segments declined significantly with distance from land (Fig. 8). All Reef Tract and Offshore Tortugas sites had comparably low turbidity levels (~0.2 NTU). Highest Alongshore turbidity was found in the Middle Keys (median 1.3 NTU). No significant differences in Alongshore turbidity in the Tortugas, Lower, and Upper Keys were observed (~0.6 NTU).

Differences in median salinity with distance offshore were small; trends in salinity variability were large (Fig. 8). Salinity from Alongshore to Reef Tract increased significantly in the Upper Keys whereas in the Lower Keys, salinity actually decreased offshore. No significant change in salinity was observed along Middle Keys, Marquesas, or Tortugas transects. In all segments, Alongshore salinities were much more variable than those of Reef Tract and Offshore. Reef Tract and Tortugas Offshore salinities were not significantly different, therefore, Alongshore salinity in the Lower Keys was higher than local seawater values while Alongshore salinity in the Upper Keys was depressed relative to local seawater values.

Stations Grouped By Shore Type

Ocean-side transects showed marked differences in water quality when grouped by shore type (Fig. 9). Transects situated on open channels (Pass) through the Keys were elevated in NO_3^{--}, NH_4^+, TP, $Si(OH)_4$, CHLA, TOC, and turbidity relative to those against the island chain (Land). Both salinity and temperature were significantly lower in Pass transects than for Land. Although these differences were statistically significant, the absolute differences were very small being only fractional. We also found that these effects diminished rapidly with distance offshore (data not shown). Interestingly, those transects located along Biscayne National Park (Old Rhodes Key, Elliot Key, the Safety Valve) were lowest of all for NO_3^-, NH_4^+, TP, $Si(OH)_4$, and CHLA.

Objective Classification Analysis

PCA identified four composite variables (hereafter called PC1, PC2, etc.) that passed the rule N for significance at $P<0.05$ (Overland and Preisendorfer 1982). The factor loadings, as correlations between the original variables and the principal components (Table 2), indicate four separate modes of variation in the data. PC1 had high factor loadings for NO_3^-, NO_2^-, NH_4^+, and SRP and was called the "Dissolved Inorganic Nutrient" component. PC2 included salinity, temperature, and DO concentration and was called the "Physical) component. TP, APA, CHLA, and turbidity made up PC3 and was therefore designated as the "Phytoplankton" component. The covariance of TP with CHLA implies that, in many areas, phytoplankton biomass may be limited by phosphorus availability. This is contrary to much of the literature on the subject which usually ascribes nitrogen as being the limiting factor for phytoplankton production in coastal oceans. Finally, TON, TOC, and $Si(OH)_4$ were included in PC4 as the "Terrestrial" component. These four principal components accounted for 58.4 % of the total variance of the original variables.

Spatial distributions of the mean factor score for each station indicated how the average water quality varied over the study area. The "Dissolved Inorganic Nutrient" component had two peaks: in the Backcountry and bayside of the Middle Keys (Fig. 10). The "Physical" component showed lower loadings in the alongshore Upper Keys and bayside Sluiceway extending through most Atlantic sites of the Middle and Lower Keys (Fig. 11). The "phytoplankton" component described a N to S gradient in the Backcountry and Sluiceway which extended west across the northern Marquesas (Fig. 12). Finally, the "Terrestrial" component was highest in eastern Sluiceway extending into the Backcountry and was also distributed as a gradient away from land on the Atlantic side of the Keys (Fig. 13).

The SD of the factor scores at each station indicated the degree of variability of each principal component during the 5 years of monitoring. The "Dissolved Inorganic Nutrient" component was relatively consistent across the study area, with the exception of high variability at two sites in the Sluiceway (Fig. 14). Contrary to the mean, the SD of the "Physical" component showed higher loadings in the alongshore Upper Keys and bayside Sluiceway extending through most Atlantic sites of the Middle and Lower Keys (Fig. 15). Both mean and SD of the "Phytoplankton" component described a N to S gradient in the Backcountry and Sluiceway which extended west across the northern Marquesas (Fig. 16). Finally, the "Terrestrial" component showed peaks in eastern Sluiceway and interior Backcountry and was also distributed as a gradient away from land on the Atlantic side of the Middle Keys (Fig. 17).

The k-means clustering algorithm used the mean and SD of the four factor scores of each station to classify all 150 sampling sites into 7 groups having robust correspondence in water quality (Fig. 18). Water quality characteristics at 2 sites in the Sluiceway (Bullfrog Banks and Bamboo Key, Cluster 1- ●) were sufficiently different so as to be a cluster of their own. As mentioned previously, these two sites had very high variability in the "Dissolved Inorganic Nutrient" component (Fig. 14). Two other stations in the northern Sluiceway clustered out together (Cluster 5 - ●) independent of any other sites. These sites displayed elevated mean $Si(OH)_4$ and highest variability in the "Phytoplankton" component (Fig. 16) which were probably responsible for the clustering. Both these clusters were relative outliers compared to the rest of the data and are excluded from the following discussion.

The bulk of the stations fell into 5 large clusters (2, 3, 4, 6, and 7) which described a gradient of water quality throughout the FKNMS. Although the differences among them were very subtle, they were statistically significant. OCA allowed us to say that the overall nutrient gradient, from highest to lowest concentrations, was cluster 7>6>3>2>4. Cluster 7 (●) was composed primarily those nine stations located in the southern Backcountry area. Compared to the other groups (Fig. 19), it was highest in NO_2^-, NH_4^+, TON, SRP, APA, TOC, salinity, DO, and especially NO_3^-. The fact that salinity was highest in this area implies that the shallow nature and relatively restricted hydrology (longer water residence time)of the region had much to do with water quality status. We expect that benthic flux of nutrients might be very important in such a shallow area. The same factors which make this region the most probable area to see elevated nutrient concentrations also make it vulnerable to anthropogenic impacts. Any nutrient inputs from developed lands would be retained in the system rather than being mixed and transported out.

Cluster 3 (●) was made up of alongshore stations in the Upper and Middle Keys as well as sites in the eastern Sluiceway (Fig. 18). The main difference in water quality between Cluster 7 and 3 was that Cluster 3 had higher $Si(OH)_4$ concentrations and was lower in NO_3^- (Fig. 19). As $Si(OH)_4$ has been shown to be used a semi-conservative tracer of freshwater in this system, one of the differences between Cluster 7 and 3 is proximity to freshwater sources from the Everglades. Therefore, even though both clusters show similar elevated nutrient concentrations, the sources of nutrients are different.

Cluster 6 (●) was made up of 20 stations on the north side of the Backcountry extending west over the northern Marquesas (Fig. 18). Cluster 6 was higher than Clusters 7 and 3 in TP, CHLA, and turbidity but lower in other nutrients which implies that the TP was not derived from local terrestrial sources. This is the area most heavily influenced by advection of Shelf waters.

Cluster 2 (●) and 4 (●) were the most similar in terms of water quality and were distributed widely throughout the Atlantic side of the Keys and Tortugas. Interestingly, almost all the sites off the Middle and Lower Keys belonged to Cluster 2 while those off the Upper Keys and Tortugas belonged to Cluster 4. Both groups were very low in nutrients, CHLA, and turbidity; the important difference was that Cluster 4 was slightly lower in most nutrients and had slightly lower water temperature than Cluster 2.

Time Series Analysis

We did not expect to see any temporal trends in the data because of the short data record (only 21 points on the graph), the usually high variability of the data, and the potential interference of a poorly resolved seasonal signal. This was true for most measured variables except TP, NO_3^-, and TON. Trends were tested using simple regression and considered significant if the slope was different than zero at $P<0.05$. We included data for the Shelf in the analysis to gain more spatial representation.

TP at many sites displayed significant increasing trends which were remarkably linear and showed little seasonality (e.g. Fig. 20). Rates of increase ranged from 0.01-0.07 $\mu M\ yr^{-1}$ (Table 3) which was especially noteworthy considering initial concentrations were ~0.2 µM. In many cases TP concentrations doubled or even tripled over the 6 years of sampling. On a spatial basis, increases in TP occurred in the northern Shelf, Tortugas, Backcountry, Lower Keys, and portions of the Middle and Upper Keys (Fig. 21). The effect of increased TP on the phytoplankton biomass was not shown to be significant as no concurrent increases in CHLA were observed. The trend in TP was system wide and occurred outside the FKNMS on the SW Shelf as well.

Trends in NO_3^- were also evident in the data (Fig. 22). There seemed to be more of a seasonal trend to the data but it was not quantified. Rates of increase ranged from 0.04-0.18 $\mu M\ yr^{-1}$ (Table 3). These are large increases in NO_3^- concentrations; in many cases NO_3^- went from <0.05 to >1 µM. Most of the increases occurred in the Shelf, Tortugas, Marquesas, Lower Keys, and Upper Keys (Fig. 23).

Contrary to increases in NO_3^-, TON declined at many sites over the period of record (Fig. 24). Decreases ranged from -0.7 to –2.7 $\mu M\ yr^{-1}$ and were more modest as compared to ambient TON concentrations. Most of the decreases occurred in the Shelf, Sluiceway, Lower Keys, and Upper Keys (Fig. 25). It is possible that loss of TON was due to biological conversion to NO_3^-, but there was no significant correspondence between TON declines and NO_3^- increases. Most probably, these trends were driven by large scale circulation patterns.

Discussion

Distinguishing internal from external sources of nutrients in the FKNMS is a difficult task. The finer discrimination of internal sources into natural and anthropogenic inputs is even more difficult. Most of the important anthropogenic inputs are regulated and most likely controlled by management activities, however, recent studies have shown that nutrients from shallow sewage injection wells may be leaking into nearshore surface waters (Corbett et al. 1999). Advective transport of nutrients through the FKNMS was not measured by the existing fixed sampling plan. However, nutrient distribution patterns may be compared to the regional circulation regimes in an effort to visualize the contribution of external sources and advective transport to internal water quality of the FKNMS.

Circulation in coastal South Florida is dominated by regional currents such as the Loop Current, Florida Current, and Tortugas Gyre and by local transport via Hawk Channel and along-shore Shelf movements (Klein and Orlando 1994). Regional currents may influence water quality over large areas by the advection of external surface water masses into and through the FKNMS (Lee et al. 1994) and by the intrusion of deep offshore ocean waters onto the reef tract as internal bores (Leichter et al. 1996). Local currents become more important in the mixing and transport of freshwater and nutrients from terrestrial sources (Smith 1994; Pitts 1997).

Spatial patterns of salinity in coastal South Florida show these major sources of freshwater to have more than just local impacts (Fig. 3 and Appendix). In Biscayne Bay, freshwater is released through the canal system operated by the South Florida Water Management District; the impact is clearly seen to affect northern Key Largo by causing episodic depressions in salinity at alongshore sites. Freshwater entering NE Florida Bay via overland flow from Taylor Slough and C-111 basin mix in a SW direction. The extent of influence of freshwater from Florida Bay on alongshore salinity in the Keys is less than that of Biscayne Bay but it is more episodic. Transport of low salinity water from Florida Bay does not affect the Middle Keys sites enough to depress the median salinity in this region but is manifested as increased variability. On the west coast, the large influence of the Shark River Slough, which drains the bulk of the Everglades and exits through the Whitewater Bay - Ten Thousand Islands mangrove complex, is clearly seen to impact the Shelf waters (Appendix). The mixing of Shelf waters with the Gulf of Mexico produces a salinity gradient in a SW direction which extends out to Key West. This freshwater source does not affect the Backcountry because of its shallow nature but instead follows a trajectory of entering western Florida Bay and exiting out through the channels in the Middle Keys (Smith 1994). This net transport of lower salinity water from mainland to reef in open channels through the Keys is observed as an increase in the range and variability of salinity rather than as a large depression in salinity.

In addition to surface currents there is evidence that internal tidal bores regularly impact the Key Largo reef tract (Leichter et al. 1996; Leichter and Miller 1999). Internal bores are episodes of higher density, deep water intrusion onto the shallower shelf or reef tract. Depending on their energy, internal tidal bores can promote stratification of the water column or cause complete vertical mixing as a breaking internal wave of subthermocline water. The graph of median $\Delta\sigma_t$ (Fig. 26), shows that the SW area of the Tortugas segment tends to experience the greatest frequency of stratification events. The decreased temperature and increased salinity in bottom waters from intrusion of deeper denser oceanic waters to this region may also account for increases in NO_3^-, TP, and SRP in these bottom waters as well. For example, in April 1998 a mass of colder, nutrient laden water from the Gulf of Mexico moved up onto the Tortugas reefs and fueled a large benthic macroalgae bloom (J. Porter, pers. comm.). This event was observed throughout most of the eastern Gulf as far north as Pensacola. At the two most SW stations, temperatures dropped ~4°C, NO_3^- increased 3 orders of magnitude, SRP and $Si(OH)_4$ increased by a factor of 100, while TP, turbidity, and in vivo CHLA specific fluorescence (measured via CTD) all doubled. As there was only a small increase in NH_4^+ during this event we believe the general case of elevated NH_4^+ and turbidity found in bottom waters throughout the FKNMS is most probably due to benthic flux and resuspension and not to subthermocline advection.

Surface $Si(OH)_4$ concentrations exhibited a pattern similar to salinity (Appendix). The source of $Si(OH)_4$ in this geologic area of carbonate rock and sediments is from siliceous periphyton (diatoms) growing in the Shark River Slough, Taylor Slough, and C-111 basin watersheds. Unlike the Mississippi River plume with CHLA concentrations of 76 µg l^{-1} (Nelson and Dortch 1996), phytoplankton biomass on the Shelf (1-2 $\mu g\ l^{-1}$ CHLA) was not sufficient to account for the depletion of $Si(OH)_4$ in this area. Therefore, $Si(OH)_4$ concentrations on the Shelf were depleted by mixing alone allowing $Si(OH)_4$ to be used as a semi-conservative tracer of freshwater in this system (Ryther et al. 1967; Moore et al. 1986). Unlike Florida Bay and the west coast, there was very little $Si(OH)_4$ loading to southern Biscayne Bay, mostly because the source of freshwater to this system is from canals which drain agricultural and urban areas of Dade County.

In the Lower and Middle Keys, it is clear that the source of $Si(OH)_4$ to the nearshore Atlantic waters is through the Sluiceway and Backcountry. $Si(OH)_4$ concentrations near the coast were elevated relative to the reef tract with much higher concentrations occurring in the Lower and Middle Keys than the Upper Keys (Fig. 7). There is an interesting peak in $Si(OH)_4$ concentration in an area of the Sluiceway which is densely covered with the seagrass, *Syringodium* (Fourqurean this volume). We are unsure as to the source but postulate that it may be due to benthic flux.

Visualization of spatial patterns of NO_3^- concentration over South Florida waters provide an extended view of source gradients over the region (Appendix). Biscayne Bay, Florida Bay, and the Shark River area of the west coast exhibited high NO_3^- concentrations relative to the FKNMS and Shelf. Elevated NO_3^- in Biscayne Bay is the result of loading from both the canal drainage system and from inshore groundwater (Alleman et al. 1995, Meeder et al. 1997). The source of NO_3^- to Florida Bay is the Taylor Slough and C-111 basin (Boyer and Jones, 1999; Rudnick et al., 1999) while the Shark River Slough impacts the west coast mangrove rivers and out onto the Shelf (Rudnick et al., 1999). We speculate that in both cases, elevated NO_3^- concentrations are the result of N_2 fixation/nitrification within the mangroves (Pelegri and Twilley 1998). The oceanside transects off the uninhabited Upper Keys (off Biscayne Bay in Seg. 9) exhibited the lowest alongshore NO_3^- compared to the Middle and Lower Keys. A similar pattern was observed in a previous transect survey from these areas (Szmant and Forrester 1996). They also showed an inshore elevation of NO_3^- relative to Hawk Channel and the reef tract which is also demonstrated in our analysis (Fig. 7). Interestingly, NO_3^- concentrations in all stations in the Tortugas transect were similar to those of reef tract sites in the mainland Keys; there was no inshore elevation of NO_3^- on the transect off uninhabited Loggerhead Key. We suggest this source of NO_3^- in the Keys is the due to human shoreline development.

Figure 7 also shows that a distinct intensification of NO_3^- occurs in the Backcountry region. Part of this increase may due to a local sources of NO_3^-, i.e. septic systems and stormwater runoff around Big Pine Key (Lapointe and Clark 1992). However, there is another area, the Snipe Keys, that also exhibits high NO_3^- which is uninhabited by man which rules out the premise of septic systems being the only source of NO_3^- in this area. It is important to note that the Backcountry area is very shallow (~0.5 m) and hydraulically isolated from the Shelf and Atlantic which results in its having a relatively long water residence time. Elevated NO_3^- concentrations may be partially due to simple evaporative concentration as is seen in locally elevated salinity values. Another possibility is a contribution of benthic N_2 fixation/nitrification in this very shallow area.

NH_4^+ concentrations were distributed in a similar manner as NO_3^- with highest levels occurring in Florida Bay, the Ten Thousand Islands, and the Backcountry (data not shown). NH_4^+ concentrations were very low in Biscayne Bay because it is not a major component of loading from the canal drainage system. NH_4^+ also showed similarities with NO_3^- in its spatial distribution, being lowest in the Upper Keys and highest inshore relative to offshore. There was no alongshore elevation of NH_4^+ concentrations in the Tortugas where levels were similar to those of reef tract sites in the mainland Keys. That the least developed portion of the Upper Keys in Biscayne National Park and uninhabited Loggerhead Key (Tortugas) exhibited lowest NO_3^- and NH_4^+ concentrations is evidence of a local anthropogenic source for both of these variables along the ocean side of the Upper, Middle, and Lower Keys. This pattern of decline offshore implies an onshore N source which is diluted with distance from land by low nutrient Atlantic Ocean waters.

Elevated DIN concentrations in the Backcountry, on the other hand, are not so easily explained. We postulate that the high concentrations found there are due to a combination of anthropogenic loading, physical entrapment, and benthic N_2 fixation. The relative contribution of these potential sources is unknown. Lapointe and Matzie (1996) have shown that stormwater and septic systems are responsible for increased DIN loading in and around Big Pine Key. The effect of increased water residence time in DIN concentration is probably small. Salinities in this area were only 1-2 psu higher than local seawater which resulted in a concentration effect of only 5-6%. Benthic N_2 fixation may potentially be very important in the N budget of the Backcountry. Measured rates of N_2 fixation in a *Thalassia* bed in Biscayne Bay, having very similar physical and chemical conditions, were 540 μmol N m^{-2} d^{-1} (Capone and Taylor 1980). Without the plant community N demand, one day of N_2 fixation has the potential to generate a water column concentration of >1 μM NH_4^+ (0.5 m deep). Much of this NH_4^+ is probably nitrified and may help account for the elevated NO_3^- concentrations observed in this area as well. Clearly, N_2 fixation may be a significant component of the N budget in the Backcountry and that it may be a exported as DIN to the FKNMS in general.

Spatial patterns in TP in South Florida coastal waters were strongly driven by the west coast sources (Appendix). A small gradient in TP extended from the inshore waters of Whitewater Bay - Ten Thousand Islands mangrove complex out onto the Shelf and Tortugas. A weak gradient also extended from north central Florida Bay to the Middle Keys. Brand (1997) has postulated that groundwater from a subterranean Miocene quartz sand channel, "the river of sand", containing high levels of phosphorus is the source of TP in this region. However, little evidence of this source exists to date and field data from Florida Bay does not indicate a subterranean source (Corbett et al. 1999; Boyer and Jones unpublished data). Finally, there was no evidence of a significant terrestrial source of TP to Biscayne Bay.

In the Keys, there was evidence of elevated TP in alongshore stations of the Middle and Lower Keys but the differences were very small (Fig. 7). The Upper Keys actually showed higher TP concentrations on the reef tract than inshore implying an offshore source. Interestingly, the Tortugas area had higher TP concentrations than the Upper Keys as a result of Shelf water advection.

In South Florida coastal waters, very little of TP is found in the inorganic form (SRP - PO_4^-); most is organic P. The distribution of SRP on the west coast and Shelf was similar to that of TP with the general gradient from the west coast to Tortugas remaining (Appendix). However, the SRP distribution was distinctly different from that of TP in Florida Bay, Whitewater Bay, and Biscayne Bay. In central Florida Bay the N-S gradient previously observed for TP was highly diminished for SRP indicating that almost all the TP in central Florida Bay was in the form of organic P. It is unlikely that the source of TP to this region is from overland flow or groundwater as this is also the region that expresses highest salinity. Alternately, we hypothesize that the presence of the Flamingo channel, running parallel to the southern coastline of Cape Sable, acts as a tidal conduit for episodic advection of inshore Shelf water to enter north central Florida Bay.

Subsequent trapping and evaporation then may act to concentrate TP in this region. The second difference in P distributions was that there was a significant SRP gradient present in NE Florida Bay that was not observed for TP. The sources of SRP to this area are the Taylor Slough and C-111 basin (W. Walker per. communication; Boyer and Jones, 1999; Rudnick et al., 1999).

Whitewater Bay displayed an east-west gradient in SRP concentrations which increased with salinity leading us to conclude that the freshwater inputs from the Everglades were not a source of SRP to this area. Finally, there was evidence of a significant onshore-offshore SRP gradient in southern Biscayne Bay; most probably as a direct result of canal loading and groundwater seepage to this region (A. Lietz personal communication; Meeder et al. 1997).

Concentrations of TOC (Appendix) and TON (Appendix) are remarkably similar in pattern of distribution across the South Florida coastal hydroscape. The decreasing gradient from west coast to Tortugas was very similar to that of TP. A steep gradient with distance from land was also observed in Biscayne Bay. Both these gradients were most probably due to terrestrial loading. On the west coast, the source of TOC and TON was from the mangrove forests. Our data from this area shows that concentrations of TOC and TON increased from Everglades headwaters through the mangrove zone and then decrease with distance offshore. In Biscayne Bay, much of the TOC and TON is from agricultural land use. The high concentrations of TOC and TON found in Florida Bay were due to a combination of terrestrial loading (Boyer and Jones, 1999), in situ production by seagrass and phytoplankton, and evaporative concentration (Fourqurean et al. 1993).

Advection of Shelf and Florida Bay waters through the Sluiceway and passes accounted for this region and the inshore area of the Middle Keys as having highest TOC and TON of the FKNMS (Fig. 8). Strong offshore gradients in TOC and TON existed for all mainland Keys segments but not for the Tortugas transect. Part of this difference may be explained by the absence of mangroves in the single Tortugas transect. The higher concentrations of TOC and TON in the inshore waters of the Keys implies a terrestrial source rather than simply benthic production and sediment resuspension. Main Keys reef tract concentrations of TOC and TON were similar to those found in the Tortugas.

Much emphasis has been placed on assessing the impact of episodic phytoplankton blooms in Florida Bay on the offshore reef tract environment. Spatial patterns of CHLA concentrations showed that NW Florida Bay, Whitewater Bay, and the Ten Thousand Islands exhibited high levels of CHLA relative to Biscayne Bay, Shelf, and FKNMS (Appendix). The highest CHLA concentrations were found in west coast mangrove estuaries (up to 45 $\mu g\ l^{-1}$ in Alligator Bay, TTI). CHLA is also routinely high (~2 $\mu g\ l^{-1}$) in NW Florida Bay along the channel connecting the Shelf to Flamingo. It is interesting that CHLA concentrations are higher in the Marquesas (0.36 $\mu g\ l^{-1}$) than in other areas of the FKNMS (Fig. 8). When examined in context with the whole South Florida ecosystem, it is obvious that the Marquesas zone should be considered a continuum of the Shelf rather than a separate management entity. This shallow sandy area (often called the Quicksands) acts as a physical mixing zone between the Shelf and the Atlantic Ocean and is a highly productive area for other biota as well as it encompasses the historically rich Tortugas shrimping grounds. A CHLA concentration of 1 $\mu g\ l^{-1}$ in the water column of a reef tract might be considered an indication of eutrophication. Conversely, a similar CHLA level in the Quicksands indicates a productive ecosystem which feeds a valuable shrimp fishery.

The oceanside transects in the Upper Keys (Seg. 9) exhibited the lowest overall CHLA concentrations of any zone in the FKNMS. Ocean transects showed a slight increase in CHLA on the reef tract in this area (Fig. 8). Transects off the Middle and Lower Keys showed that a drop in CHLA occurred at reef tract sites; there was no linear decline with distance from shore (data not shown). Interestingly, CHLA concentrations in the Tortugas transect showed a similar pattern as the mainland Keys. Inshore and Hawk Channel CHLA concentrations among Middle Keys, Lower Keys and Tortugas sites were not significantly different. As inshore CHLA concentrations in the Tortugas were similar to those in the Middle and Lower Keys, we see no evidence of persistent phytoplankton bloom transport from Florida Bay. There was however some evidence of increased CHLA in those stations situated along the major passes in the Keys relative to those abutting land (Fig. 9). The differences between these two groupings were very small (0.25 vs. 0.20 $\mu g\ l^{-1}$) suggesting that although significant bloom transport events do occur, they are not routinely observed with a quarterly sampling program.

Along with TP concentration, turbidity is probably the second most important determinant of local ecosystem health. The fine grained, low density carbonate sediments in this area are easily resuspended, rapidly transported, and have high light scattering potential. High water column turbidity and transport directly affects filter feeding organisms by clogging their feeding apparatus and by increasing local sedimentation rate. Sustained high turbidity of the water column indirectly affects benthic community structure by decreasing light penetration, promoting seagrasses extinction. Large scale observations of turbidity clearly show patterns of onshore-offshore gradients which extend out onto the Shelf to the Marquesas (Appendix; Stumpf et al. 1999). In the last seven years, turbidities in Florida Bay have increased dramatically in the NE and central regions (Boyer et al. 1998) potentially as a consequence of destabilization of the sediment from seagrass die-off (Robblee et al. 1991).

Strong turbidity gradients were observed for all Keys transects (Fig. 8) but reef tract levels were remarkably similar regardless of inshore levels. High alongshore turbidity is most probably due to the shallow water column being easily resuspended by wind and wave action. Inshore stations in the Middle Keys had higher turbidity than other segments. Transects aligned with major passes had slightly greater turbidity than those against land but the difference was not statistically significant (Fig. 9). Light extinction (K_d) was highest alongshore and improved with distance from land (data not shown). This trend was expected as light extinction is directly related to water turbidity.

Using the TN:TP ratio is a relatively simple method of estimating potential nutrient limitation status of phytoplankton (Redfield 1967). Most of the South Florida hydroscape was shown to have TN:TP values >> 16:1, indicating the potential for phytoplankton to be limited by P at these sites (Appendix). The bulk of Florida Bay and both southern and northern Biscayne Bay were severely P limited, mostly as a result of high DIN concentrations. All of the FKNMS is routinely P limited using this metric. Interestingly, the Marquesas/Quicksands area was the least P limited of all zones and exhibited a significant regression between SRP and CHLA. Only in the northern Ten Thousand Islands and Shelf did N become the limiting nutrient. The south-north shift from P to N limitation observed in the west coast estuaries has been ascribed to changes in landuse and bedrock geochemistry of the watersheds (Boyer and Jones 1998). The west coast south of 25.4 N latitude is influenced by overland freshwater flow from the Everglades and Shark River Slough having very low P concentrations relative to N. Above 25.7 N latitude the bedrock geology of the watershed changes from carbonate to silicate based and landuse changes from relatively undeveloped wetland (Big Cypress Basin) to a highly urban/agricultural mix (Naples, FL).

Temporal trends in water quality showed most variables to relatively consistent from year to year. The exceptions were increased TP and NO_3^- and declining TON. We emphasize that these trends were regional phenomena and were not due solely to local inputs from the Florida Keys. These trends must also be put in perspective with other ecological changes occurring in the region. No trends in TP were observed in the western Florida Bay/Inner Shelf zone or in those FKNMS sites most influenced by transport of Florida Bay waters. During the same time period, TP concentrations in Florida Bay proper were declining (Boyer et al. 1999). The absence of TP trends in the Middle Keys may have been due to the influence of Florida Bay waters through the passes.

At this time we can only speculate as to the cause of these trends but much of the trend is driven by regional circulation patterns arising from the Loop Current which entrains water from other coastal estuaries such as the Caloosahatchee River and Tampa Bay as well as the Mississippi. That the increases have occurred in deep and shallow water stations at both the surface and bottom over a consistent period of time ruled out episodic upwelling as a major factor. We know of no data which addressed changes in internal cycling processes (benthic flux or water column cycling) over this period. However, there is some preliminary evidence that the distribution of seagrass correlates with some of the trend patterns (Fourqurean, pers. comm.). Areas where TP trends were absent were also described as areas of dense seagrass beds. One hypothesis is that the potential increase in TP concentration in these areas was modulated by uptake by the seagrass community and therefore showed no significant change.

The large scale of this monitoring program has allowed us to assemble a much more holistic view of broad physical/chemical/biological interactions occurring over the South Florida hydroscape. Much information has been gained by inference from this type of data collection program: major nutrient sources have be confirmed, relative differences in geographical determinants of water quality have been demonstrated, and large scale transport via circulation pathways have been elucidated. In addition we have shown the importance of looking "outside the box" for questions asked within. Rather than thinking of water quality monitoring as being a static, non-scientific pursuit it should be viewed as a tool for answering management questions and developing new scientific hypotheses. One of the more important management questions to be answered is "Is the water quality better or worse than it used to be?" This monitoring program based on quarterly sample intervals has revealed significant trends in TP, NO_3^-, and TON. We expect to see more trends in other variables as the database grows and we begin to tease out effects of seasonal variability.

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List of Tables

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Table 1. Summary statistics for each water quality variable in the FKNMS for the period of record. Data are summarized as median (Median), minimum value (Min.), maximum value (Max.), and number of samples (*n*).

Variable	**Depth**	**Median**	**Min.**	**Max.**	***n***
NO_3^-	Surface	0.098	0.000	4.418	3151
	Bottom	0.087	0.000	4.455	1925
NO_2^-	Surface	0.043	0.000	0.710	3160
	Bottom	0.040	0.000	1.732	1931
NH_4^+	Surface	0.337	0.000	10.320	3159
	Bottom	0.300	0.000	3.876	1929
TON	Surface	10.305	0.000	85.875	3138
	Bottom	8.302	0.000	30.889	1898
TP	Surface	0.194	0.000	1.351	3159
	Bottom	0.183	0.000	1.497	1914
SRP	Surface	0.010	0.000	0.297	3147
	Bottom	0.010	0.000	0.390	1924
APA	Surface	0.059	0.007	1.286	2996
	Bottom	0.047	0.000	0.491	1769
CHLA	Surface	0.277	0.000	15.239	3158
TOC	Surface	207.81	86.98	1653.54	3156
	Bottom	185.00	89.38	883.10	1917
$Si(OH)_4$	Surface	0.777	0.000	127.110	2859
	Bottom	0.503	0.000	30.195	1744
Turbidity	Surface	0.57	0.00	37.00	3115
	Bottom	0.50	0.00	16.90	1944
Salinity	Surface	36.2	27.7	40.3	3084
	Bottom	36.2	27.7	39.7	3057
Temperature	Surface	27.4	17.3	39.6	3091
	Bottom	26.8	17.1	36.8	3064
K_d		0.229	0.004	7.319	2869
DO_{sat}	Surface	91.1	38.1	191.6	3058
	Bottom	90.8	32.4	183.1	3012
$\Delta\sigma_t$		0.016	-4.424	6.528	3039

Table 2. Results of principal component analysis are shown as factor loadings (correlations between the raw variables and the principal components) for the first four principal components after VARIMAX rotation. For clarity, loadings with a magnitude >0.50 are shown in boldface type.

Variable	**PC1**	**PC2**	**PC3**	**PC4**
NO_3^-	**0.733**	-0.046	0.136	-0.029
NO_2^-	**0.589**	0.026	-0.052	0.430
NH_4^+	**0.670**	0.018	-0.048	0.230
TON	-0.011	0.075	0.080	**0.720**
TP	0.222	0.129	**0.605**	-0.009
SRP	**0.608**	-0.001	0.294	-0.325
APA	0.053	-0.038	**0.551**	0.361
CHLA	-0.001	-0.051	**0.813**	0.072
TOC	-0.002	0.135	0.109	**0.649**
$Si(OH)_4$	0.044	-0.072	0.052	**0.549**
Turbidity	-0.018	-0.072	**0.713**	0.176
Salinity	0.032	**0.945**	-0.033	0.008
Temp.	0.087	**0.850**	-0.114	0.157
DO	-0.122	**0.852**	0.109	-0.024
%Variance Explained	21.9	15.0	12.0	9.5

Table 3. Trend slopes estimates from time series regressions of TP, NO_3^-, and TON with time in $\mu M\ yr^{-1}$. Only significant slopes (P<0.050) are shown.

Station	Site	TP	NO_3^-	TON
200	Fowey Rocks	0.026	0.074	
201	Sands Key	0.018		-1.16
202	Bowles Bank		0.091	-1.27
203	Triumph Reef		0.051	-1.33
204	Elliott Key			-1.39
205	Margo Fish Shoal		0.145	-1.07
206	Ajax Reef		0.096	-0.95
207	Old Rhodes Key		0.082	-1.32
208	Old Rhodes Key Channel		0.092	-1.19
209	Channel Key	0.038		
210	Old Rhodes Key Reef		0.132	
211	Pennikamp G27		0.186	-1.13
212	Turtle Harbor		0.143	-0.98
213	Turtle Reef	0.018	0.104	-0.66
214	Port Elizabeth		0.094	-0.89
215	Carysfort Channel		0.094	-0.68
216	Carysfort Reef		0.080	-1.13
217	Rattlesnake Key			-1.38
218	White Bank	0.020	0.136	-0.75
219	The Elbow		0.072	-0.72
220	Radabob Key		0.074	-1.12
221	Radabob Key Channel	0.020	0.135	-0.83
222	Dixie Shoal		0.101	-0.82
223	Mosquito Bank	0.022	0.120	
224	Molasses Reef Channel	0.021	0.098	
225	Molasses Reef	0.014	0.114	
226	Tavernier Harbor	0.028		
227	Triangles	0.036		
228	Conch Reef	0.020		
229	Plantation Point	0.018		
230	The Rocks	0.018	0.047	
231	Davis Reef	0.049	0.056	
232	Upper Matecumbe Key			
233	Upper Matecumbe Chnl	0.033	0.065	
234	Fish Haven	0.023	0.061	
235	Indian Key	0.033		
236	Indian Key Channel	0.033		
237	Indian Key Offshore	0.030		-1.03

Station	Site	TP	NO_3^-	TON
238	Matecumbe Harbor			-2.08
239	Lower Matecumbe Chnl	0.021		
240	Matecumbe Offshore	0.026		
241	Long Key			-1.54
242	Long Key Channel			-1.29
243	Tennessee Reef	0.031		
244	Long Key Pass Inshore			-1.71
245	Long Key Pass Channel			
246	Long Key Pass Offshore			
247	Key Colony Beach			
248	Coffins Patch Channel		0.042	-0.97
249	Coffins Patch Offshore	0.011		
250	Seven Mile Bridge		0.093	-0.92
251	Seven Mile Br. Channel		0.076	-1.33
252	Seven Mile Br. Offshore	0.013	0.083	-1.39
253	Spanish Harbor Keys			
254	Bahia Honda Key	0.015		
255	Bahia Honda Channel		0.108	
256	Bahia Honda Offshore	0.020	0.125	-1.15
257	Long Beach	0.019	0.112	-1.54
258	Big Pine Channel	0.016	0.071	
259	Big Pine Shoal	0.014		
260	Newfound Harbor Keys	0.020		
261	American Shoal Channel	0.024		-1.10
262	Looe Key Channel	0.018		-1.34
263	Looe Key	0.020		-0.85
264	Aquarius	0.026	0.075	
265			0.120	-1.31
266	Tarpon Creek	0.030		-1.52
267	American Shoal	0.026	0.134	-1.03
268	Saddlebunch Keys	0.026		-0.85
269	West Washerwoman	0.020		-0.88
270	Maryland Shoal	0.026	0.118	-1.21
271	Boca Chica Key	0.033	0.083	-1.61
272	Eastern Sambo	0.025	0.093	
273	Eastern Sambo Offshore	0.021	0.121	
274	Boca Chica Channel	0.030	0.107	-1.24
275	Boca Chica Mid	0.030	0.127	-1.13
276	Western Sambos	0.034	0.129	
277	Key West Cut A			-0.95
278	Western Head		0.109	

Station	Site	TP	NO_3^-	TON
279	Main Ship Channel	0.021	0.079	-1.22
280	Eastern Dry Rocks	0.026	0.138	
281	Middle Ground	0.042		
282	Arsenic Bank		0.051	
283				
284	Tripod Bank		0.070	
285	Channel Key Pass	0.031		-1.63
286	Toms Harbor Cut	0.027		-1.51
287	Bamboo Banks		0.047	
288		0.033	0.062	
289	Bamboo Key		0.146	
290	Bluefish Bank		0.077	-0.99
291	Bullard Bank		0.066	
292	John Sawyer Bank			
293	Bethel Bank			
294	Red Bay Bank		0.073	-1.80
295	Bullfrog Banks		0.055	
296	W. Bahia Honda Key		0.086	
297	Cocoanut Key		0.076	
298	Harbor Key Bank			
299	Bogie Channel	0.027		
300	Little Pine Key	0.027		
301	Cutoe Key	0.029	0.064	
302	Content Passage	0.036	0.081	
303	Pine Channel	0.046		
304	Toptree Hammock Chan.	0.031		
305	Cudjoe Key	0.046	0.087	
306	Johnson Key Channel	0.038	0.092	
307	Tarpon Belly Keys	0.032		
308	Kemp Channel	0.023	0.113	
309	Snipe Point	0.029		
310	Snipe Keys	0.041		
311	Shark Key	0.032		
312	E. Harbor Key Channel	0.028	0.075	
313	Lower Harbor Keys	0.038	0.169	
314	Howe Key Channel	0.041		
315	Calda Channel	0.035	0.149	
316	Man of War Harbor	0.037	0.130	
317	Garrison Bight	0.046		
318	KY Northwest Channel	0.022	0.111	
319	N Boca Grande Channel			

Station	Site	TP	NO_3^-	TON
320	Loggerhead Marker		0.154	
321	Loggerhead Channel	0.019	0.146	
322	Satan Shoal	0.025	0.130	
323		0.027	0.182	
324	Ellis Rock	0.067	0.150	
325	SE Marquesas		0.131	
326		0.036		
327	N Quicksands			
328	Marquesas Rock	0.025	0.086	
329		0.019	0.069	-1.60
330	New Ground	0.022	0.086	-1.36
331		0.024		-1.22
332	S Quicksands			
333	Half Moon Shoal			-0.84
334			0.078	
335				
336			0.043	
337	Rebecca Shoal	0.025		
338	Garden Key	0.027	0.059	
339		0.034	0.058	
340		0.029	0.056	
341	Northwest Channel	0.027		
342	NE DTNP	0.025	0.073	
343	N DTNP	0.025	0.103	
344	Southwest Channel	0.025	0.131	-0.74
345		0.037	0.063	-0.75
346	W DTNP	0.032		
347	Loggerhead Offshore	0.028		
348	Hospital Key			
349	Logerhead Inshore		0.038	
350		0.030	0.041	-1.22

List of Figures

Figure 21. Trend slopes estimates from time series regressions of TP with time in $\mu M\ yr^{-1}$. Only significant slopes (P<0.050) are shown.

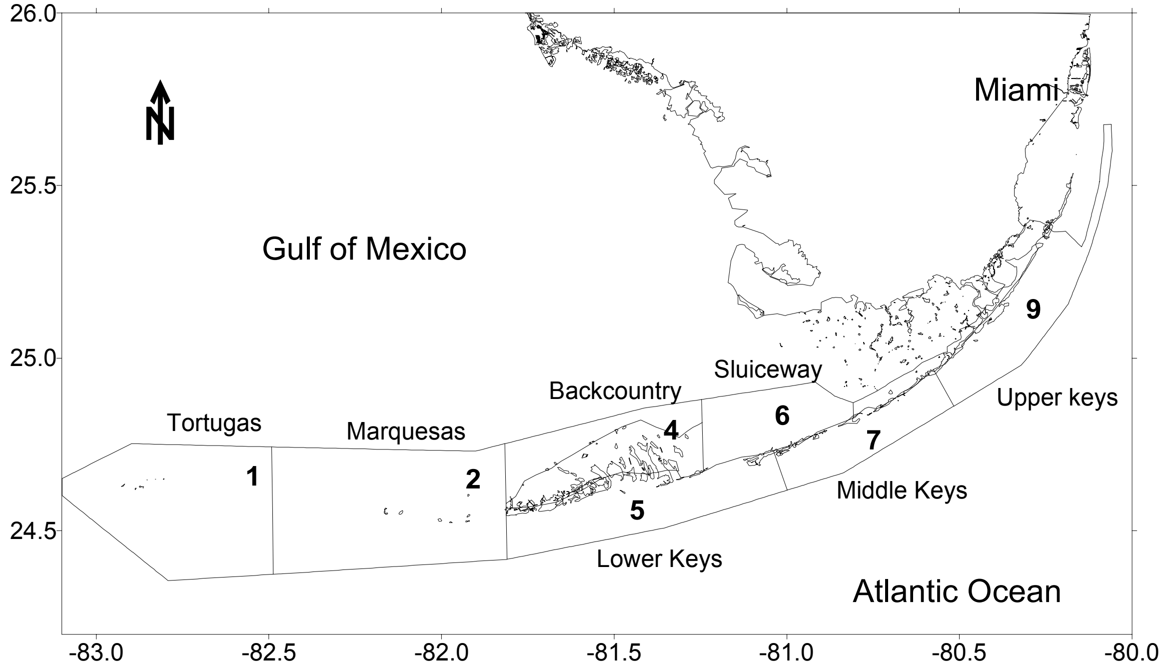
Figure 22. Representative example of time series plot of NO_3^- (μM) with time. Note the consistent increase and relative absence of seasonal variation.

Figure 23. Trend slopes estimates from time series regressions of NO_3^- with time in $\mu M\ yr^{-1}$. Only significant slopes (P<0.050) are shown.

Figure 24. Representative example of time series plot of TON (μM) with time. Note the consistent increase and relative absence of seasonal variation.

Figure 25. Trend slopes estimates from time series regressions of TON with time in $\mu M\ yr^{-1}$. Only significant slopes (P<0.050) are shown.

Figure 26. Contour map of median delta sigma-t ($\Delta\sigma_t$ in $kg\ m^{-3}$). $\Delta\sigma_t$ is the difference in density between surface and bottom waters where positive values mean bottom is more dense than surface.



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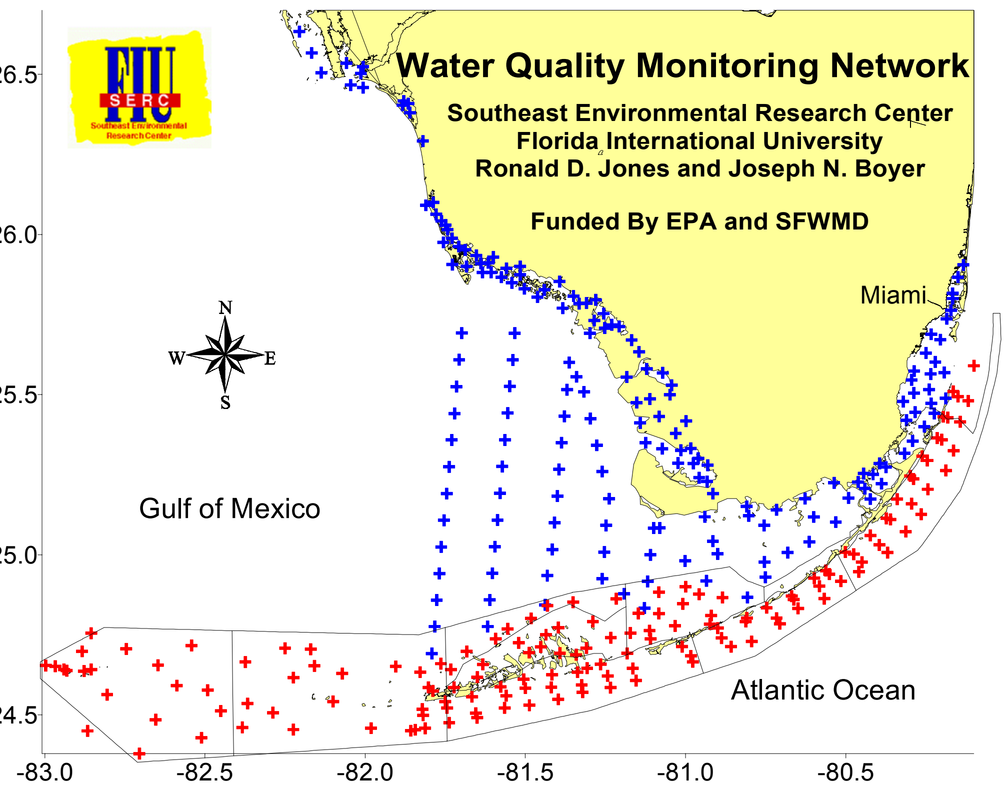

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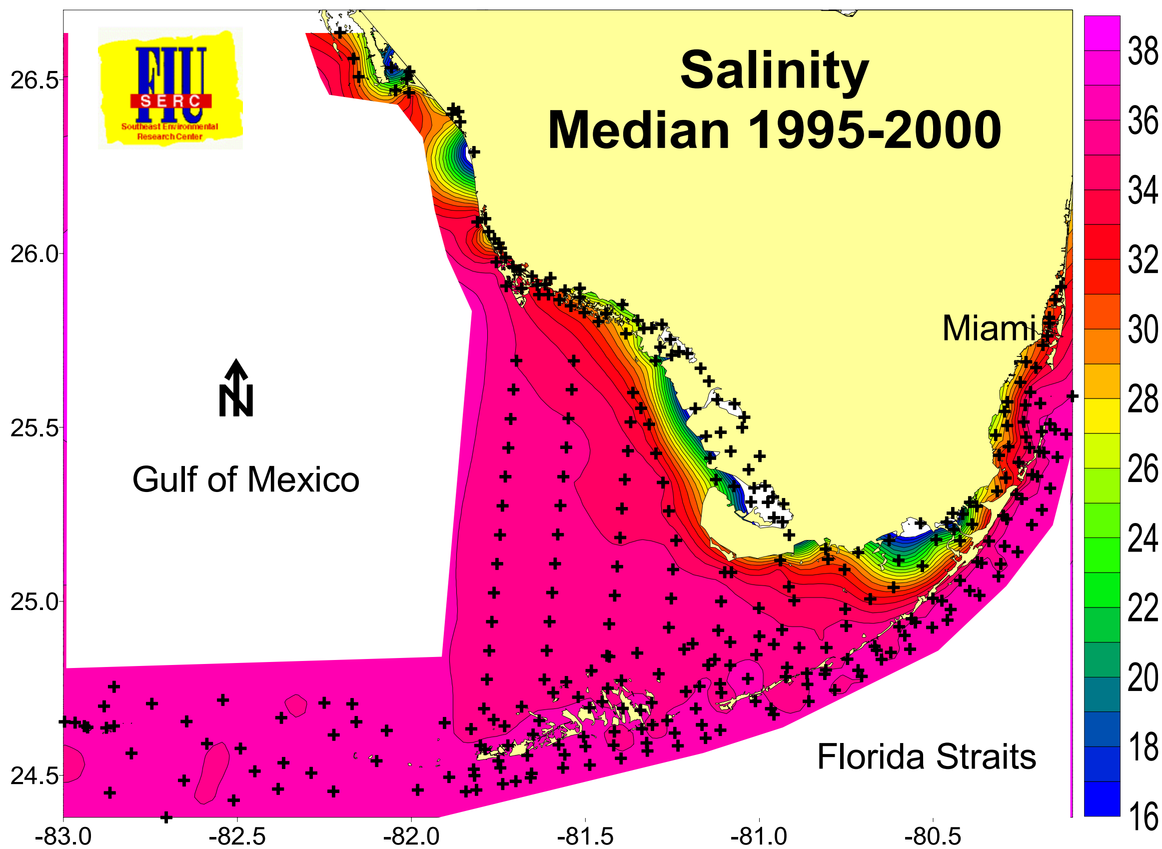
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Gulf of Mexico
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24.5
-83.0
-82.5
-82.0
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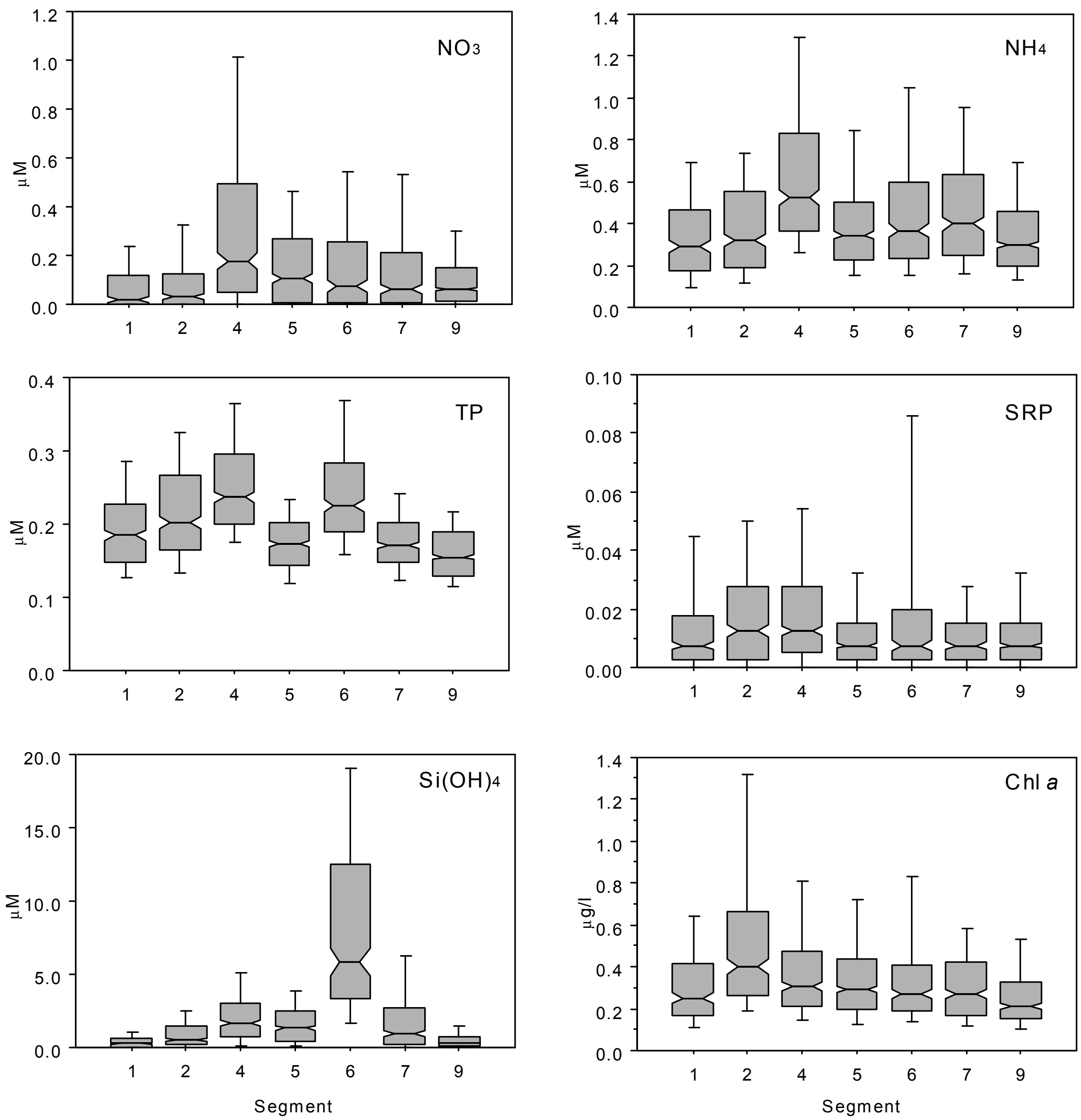
Figure 3.



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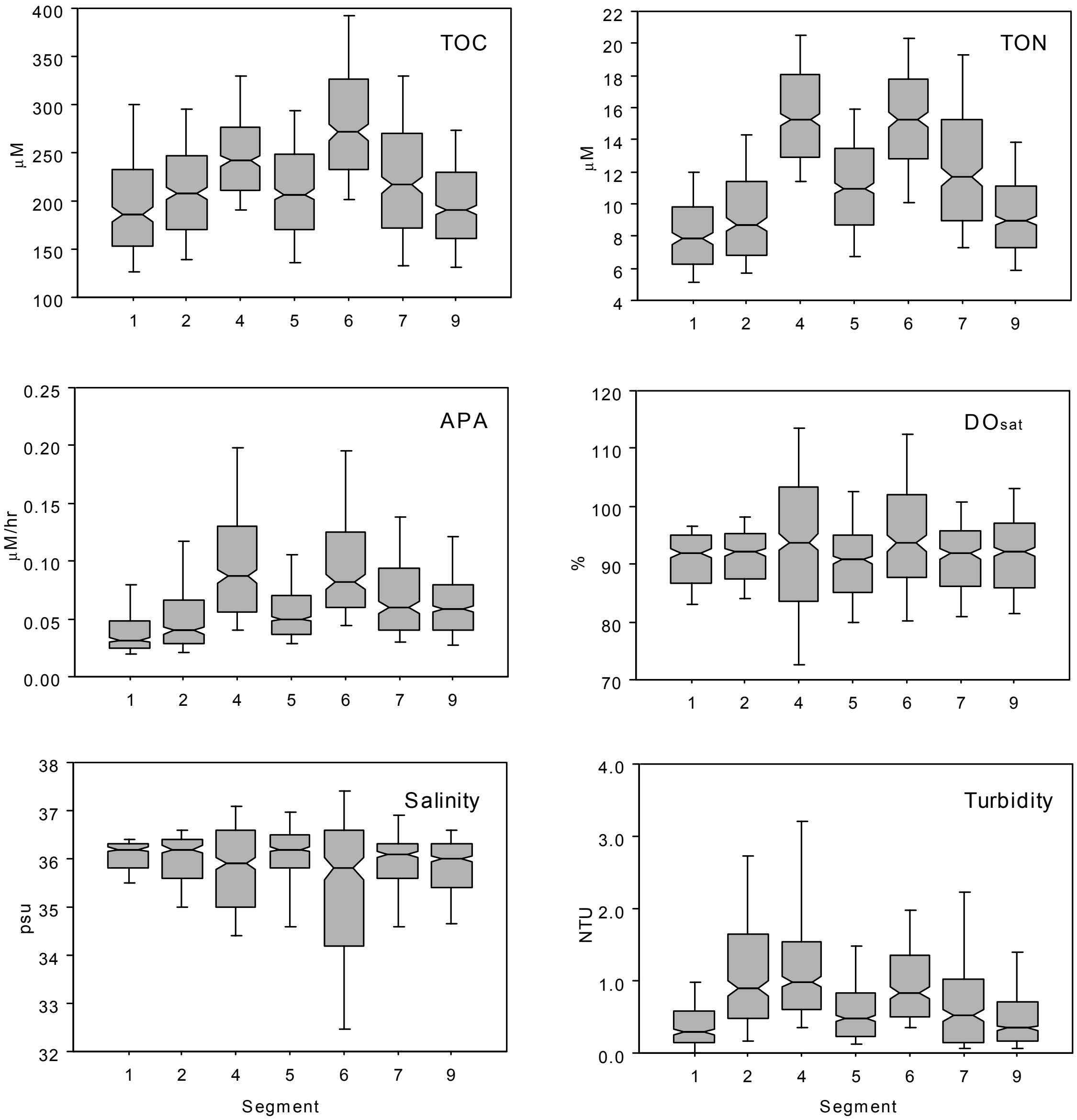
TOC
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TON
µM
APA
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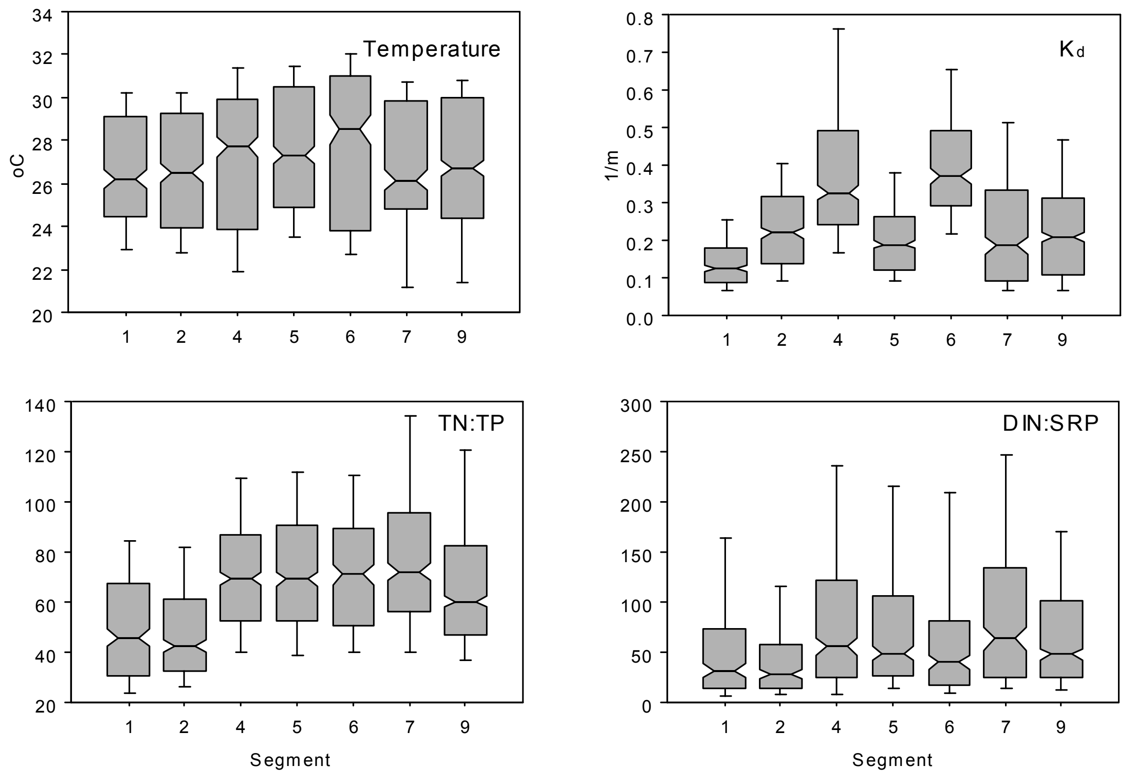
DOsat
%
Salinity
psu
Turbidity
NTU
Segment
Segment

Figure 5.



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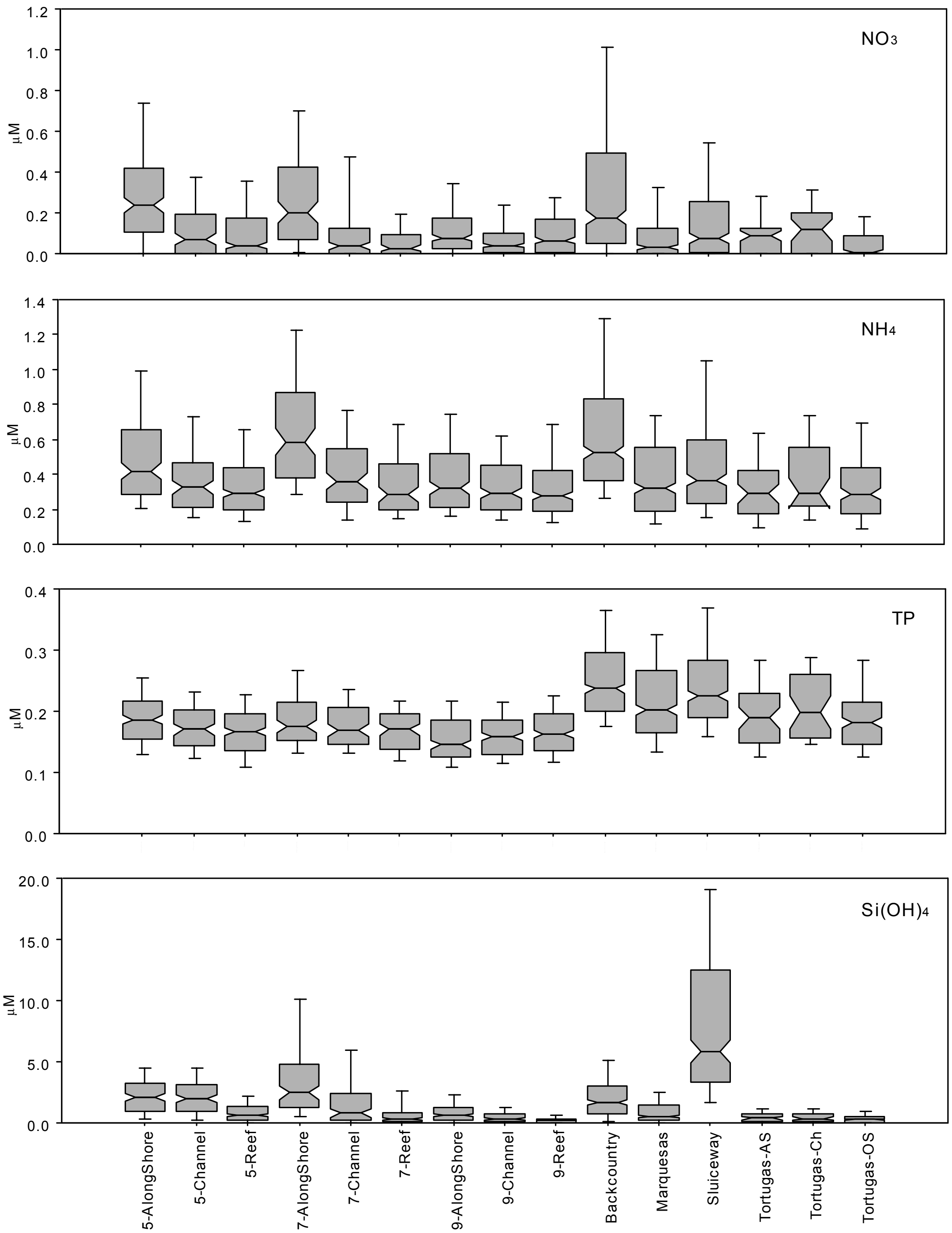
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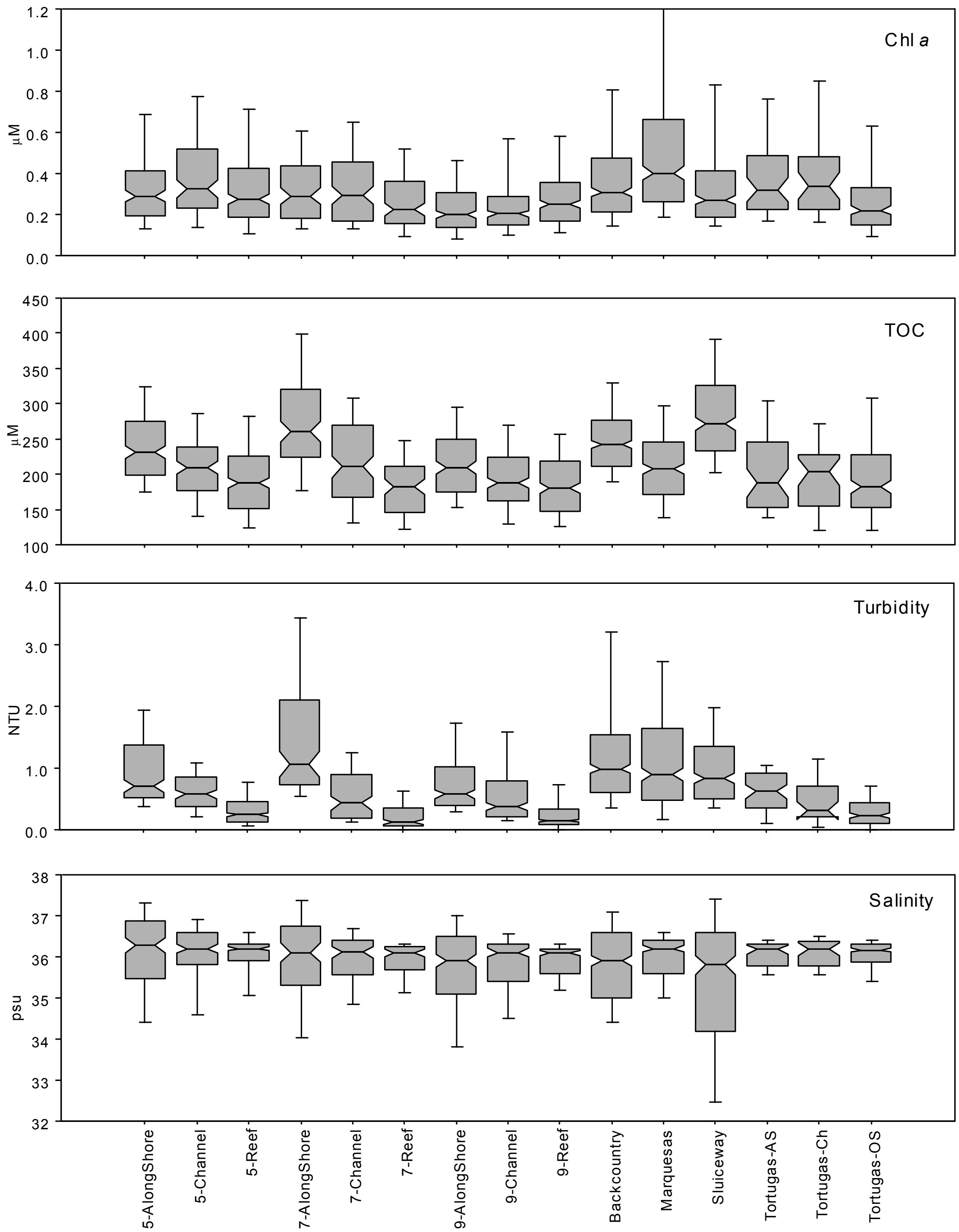
5.0
5-AlongShore
5-Channel
5-Reef
7-AlongShore
7-Channel
7-Reef
9-AlongShore
9-Channel
9-Reef
Backcountry
Marquesas
Sluiceway
Tortugas-AS
Tortugas-Ch
Tortugas-OS

Figure 7.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μM
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Turbidity
NTU
Salinity
psu
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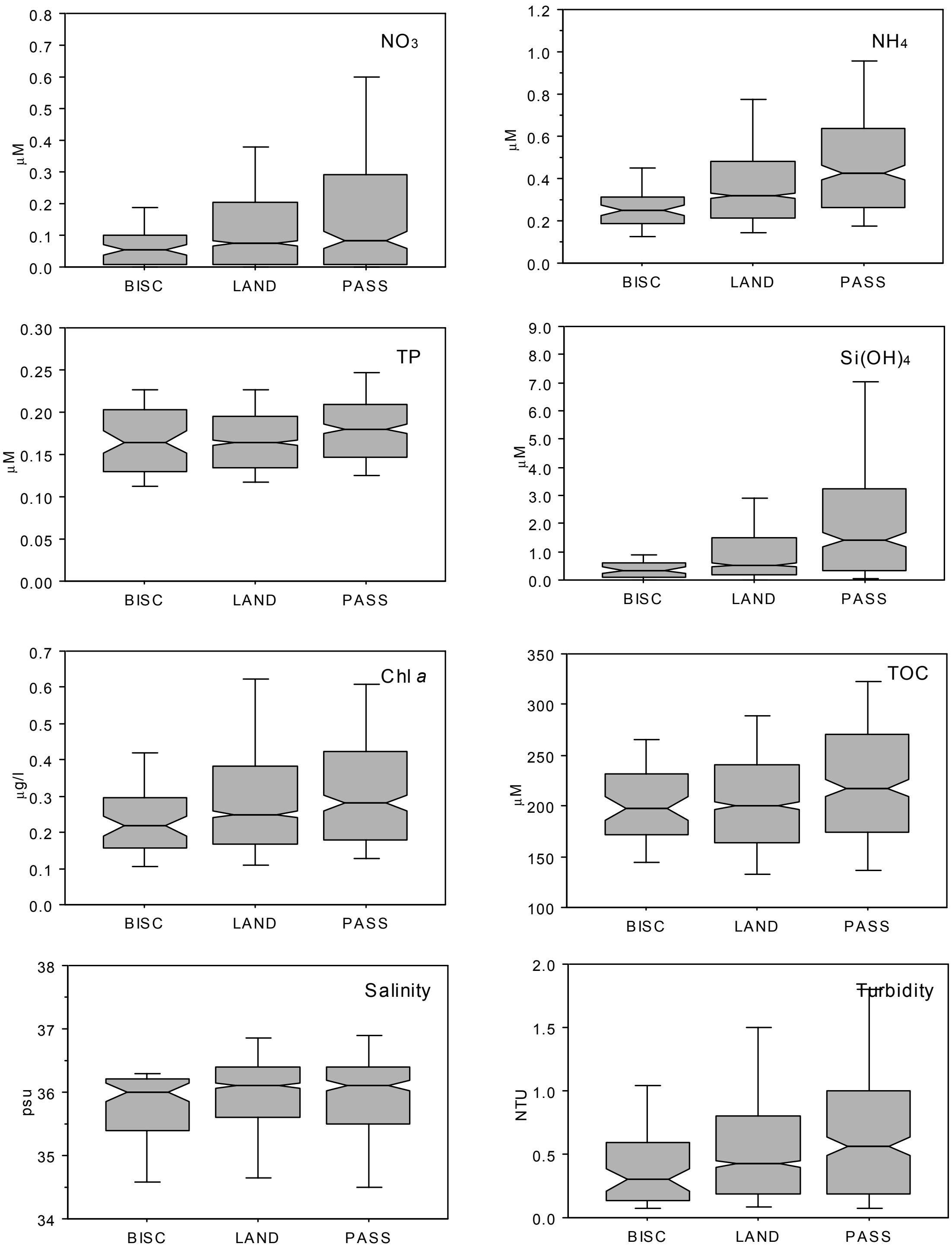
5-Channel
5-Reef
7-AlongShore
7-Channel
7-Reef
9-AlongShore
9-Channel
9-Reef
Backcountry
Marquesas
Sluiceway
Tortugas-AS
Tortugas-Ch
Tortugas-OS

Figure 8.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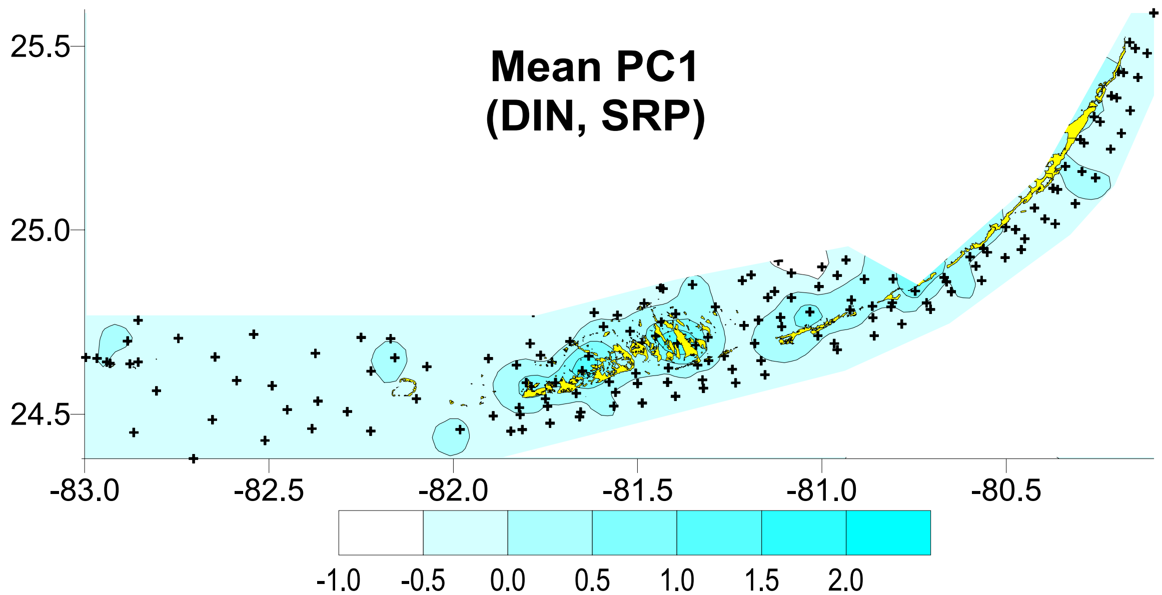
psu
NTU
BISC
LAND
PASS

Figure 9.



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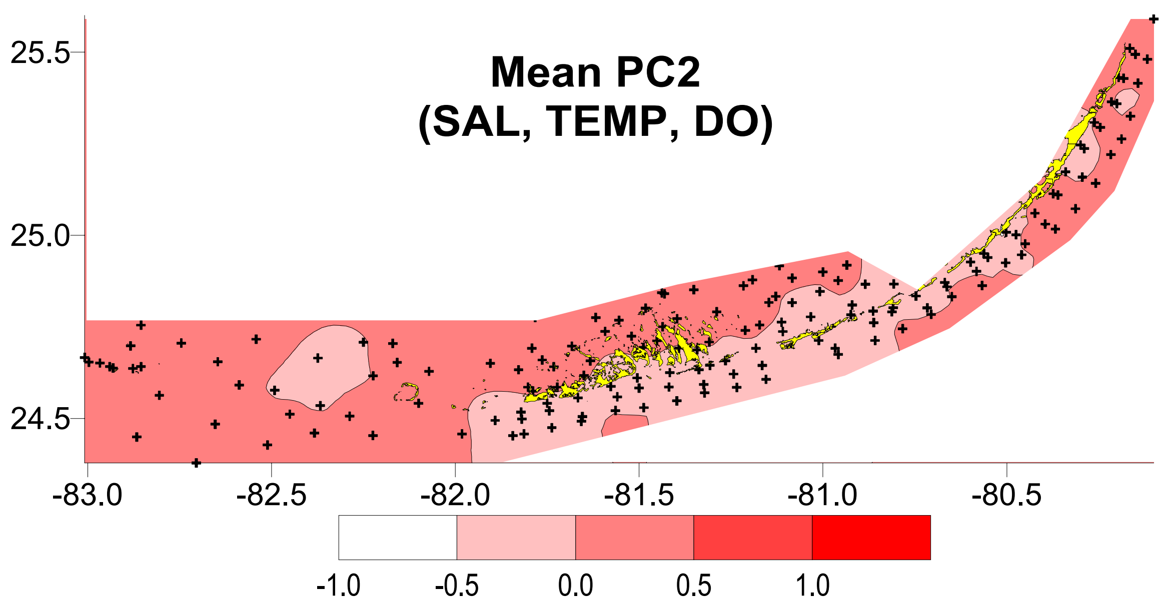

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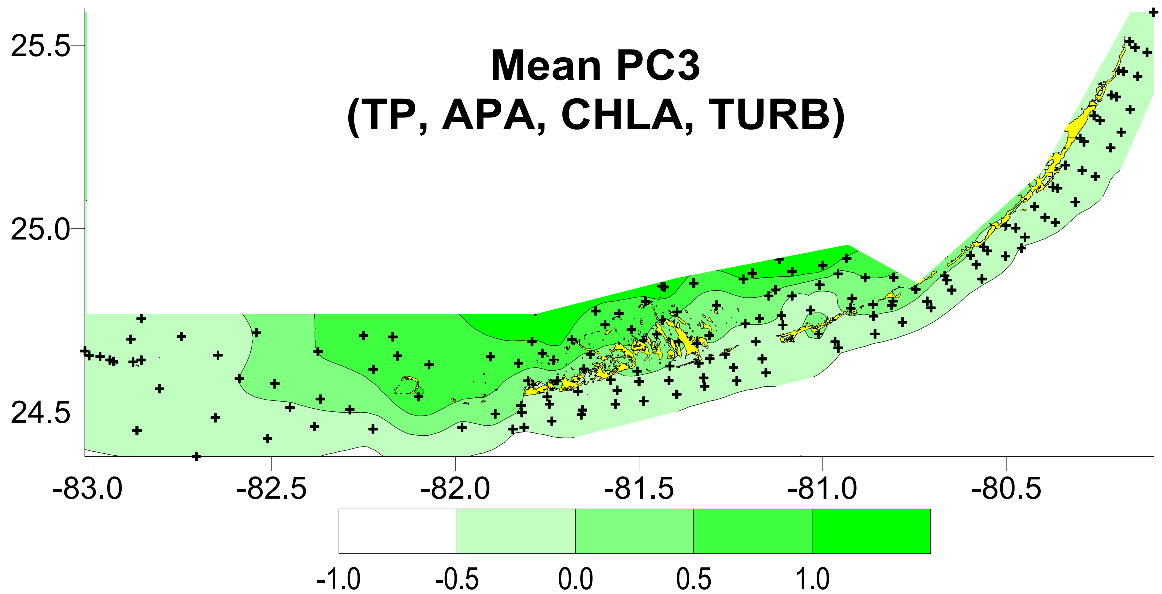

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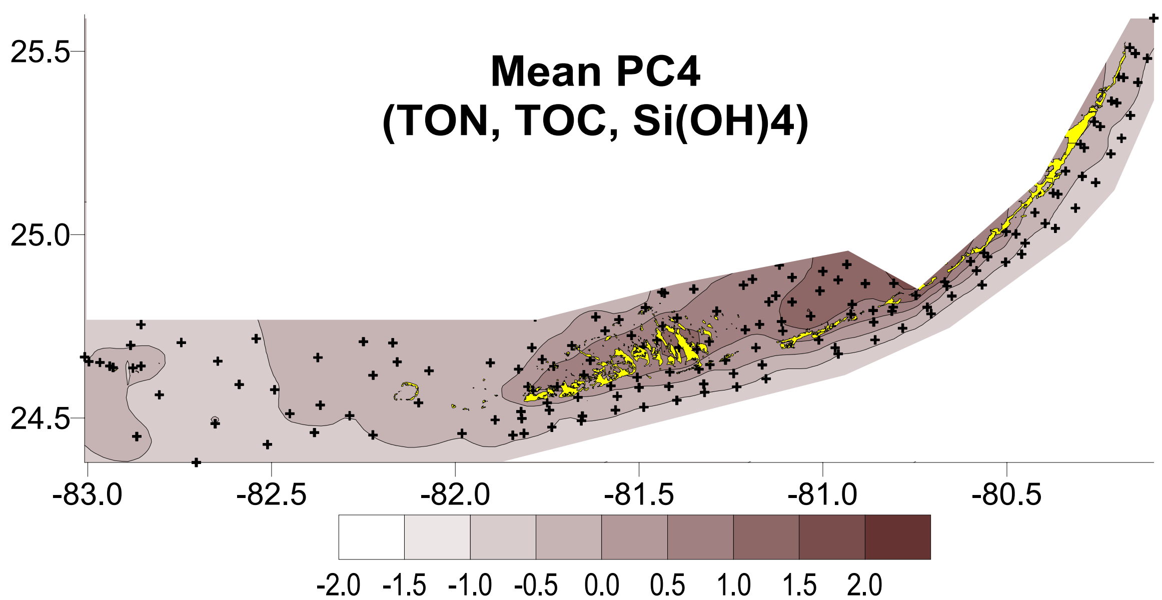

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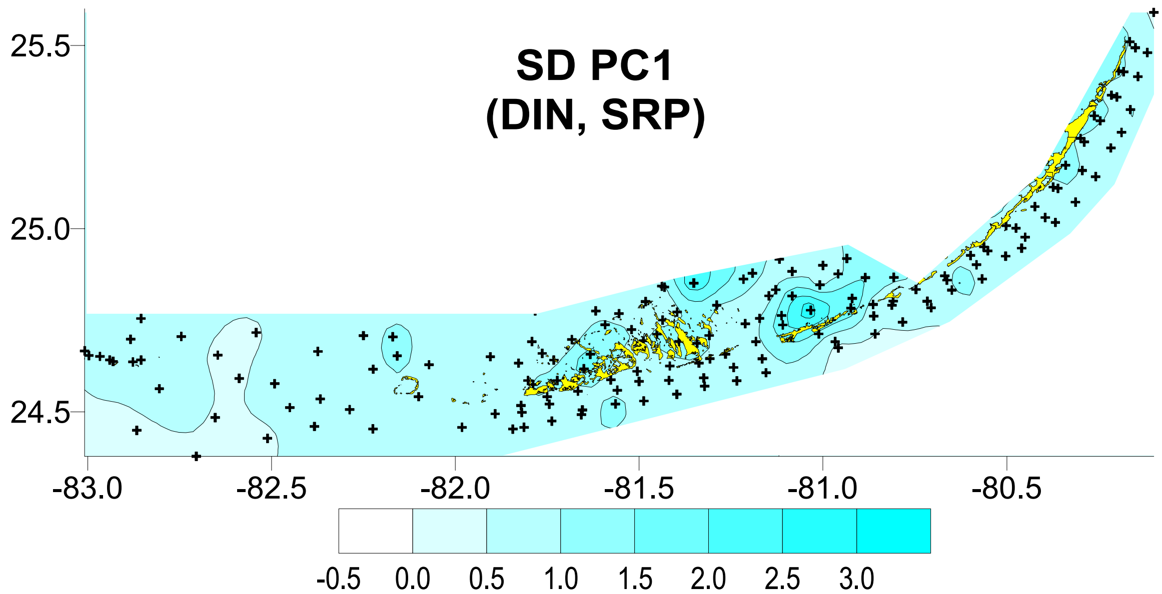

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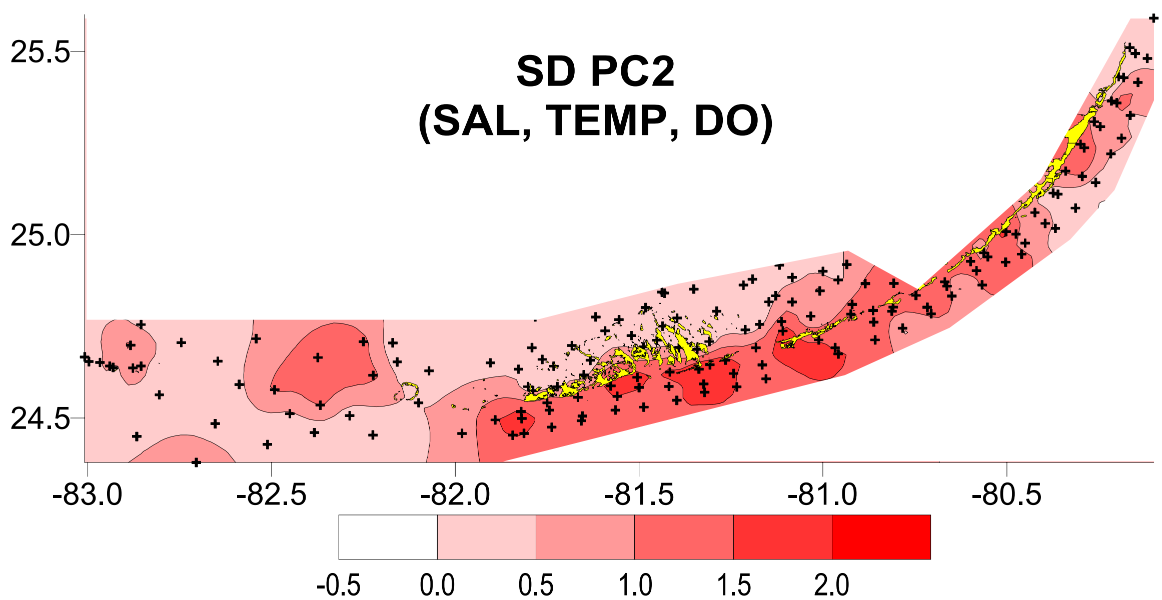

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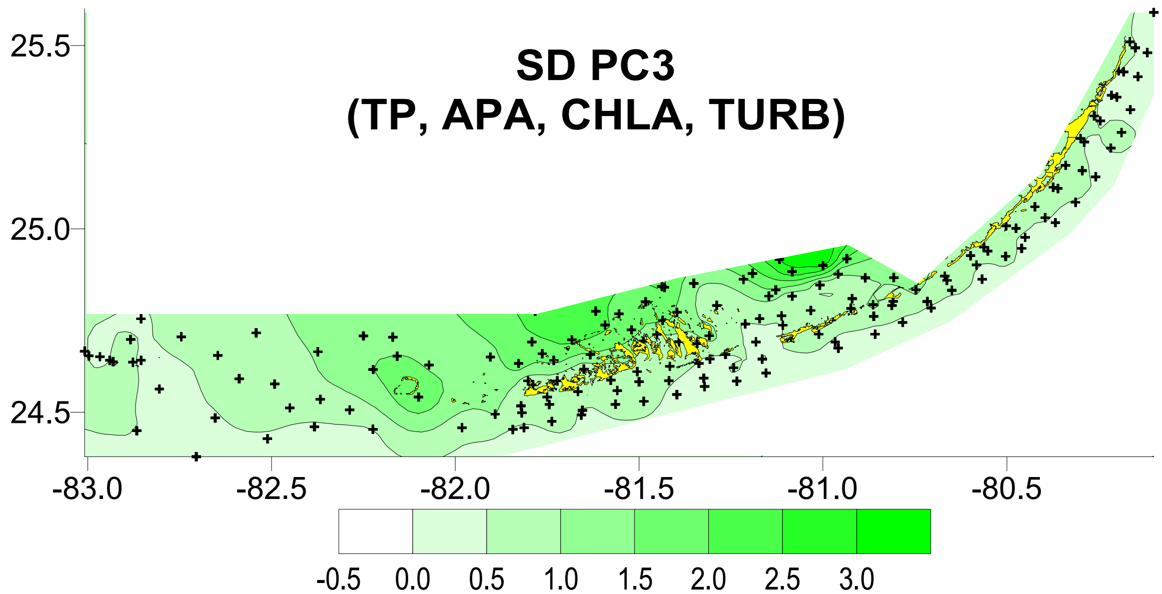

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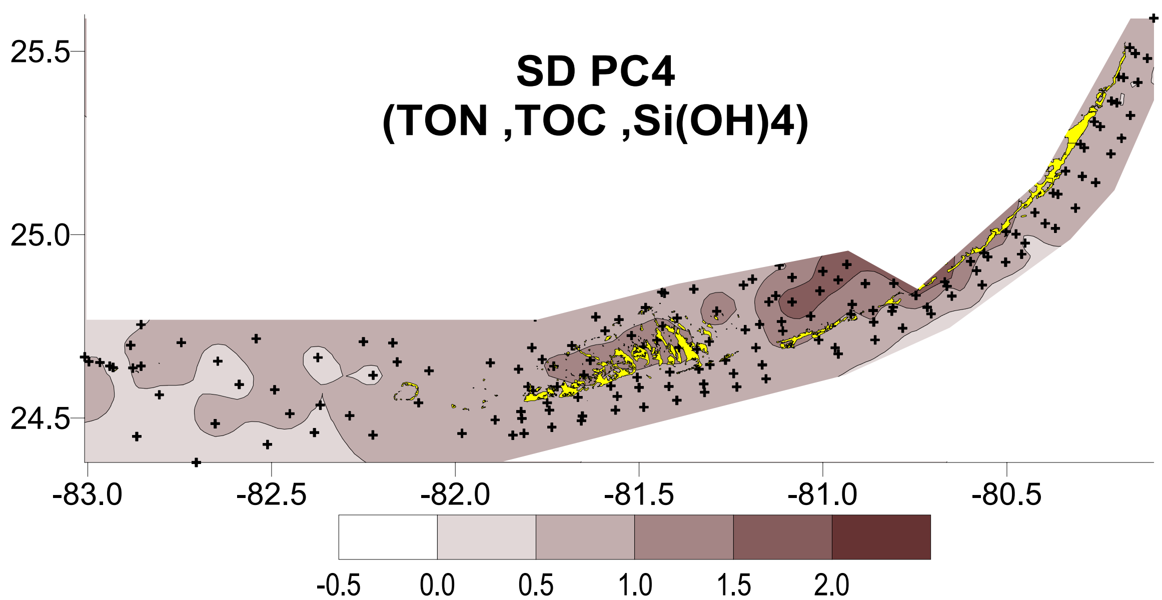
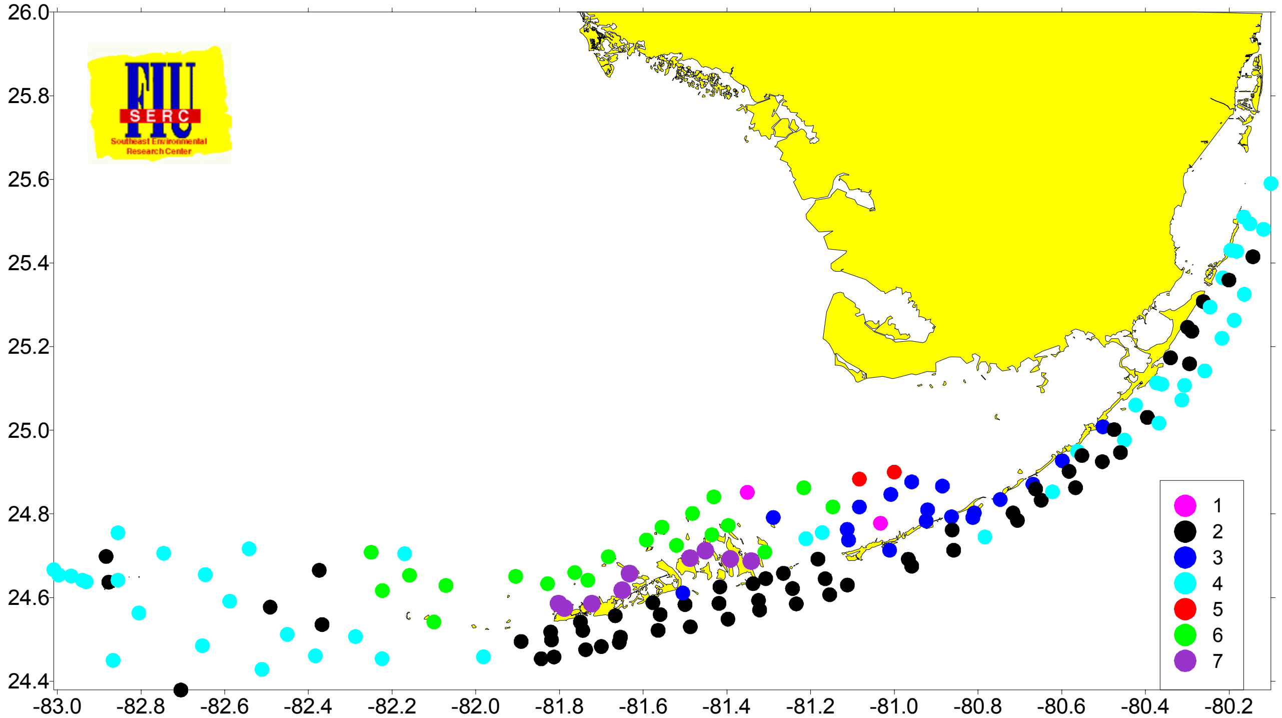


Figure 17.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FIU
SERC
Southeast Environmental Research Center
1
2
3
4
5
6
7

Figure 18.

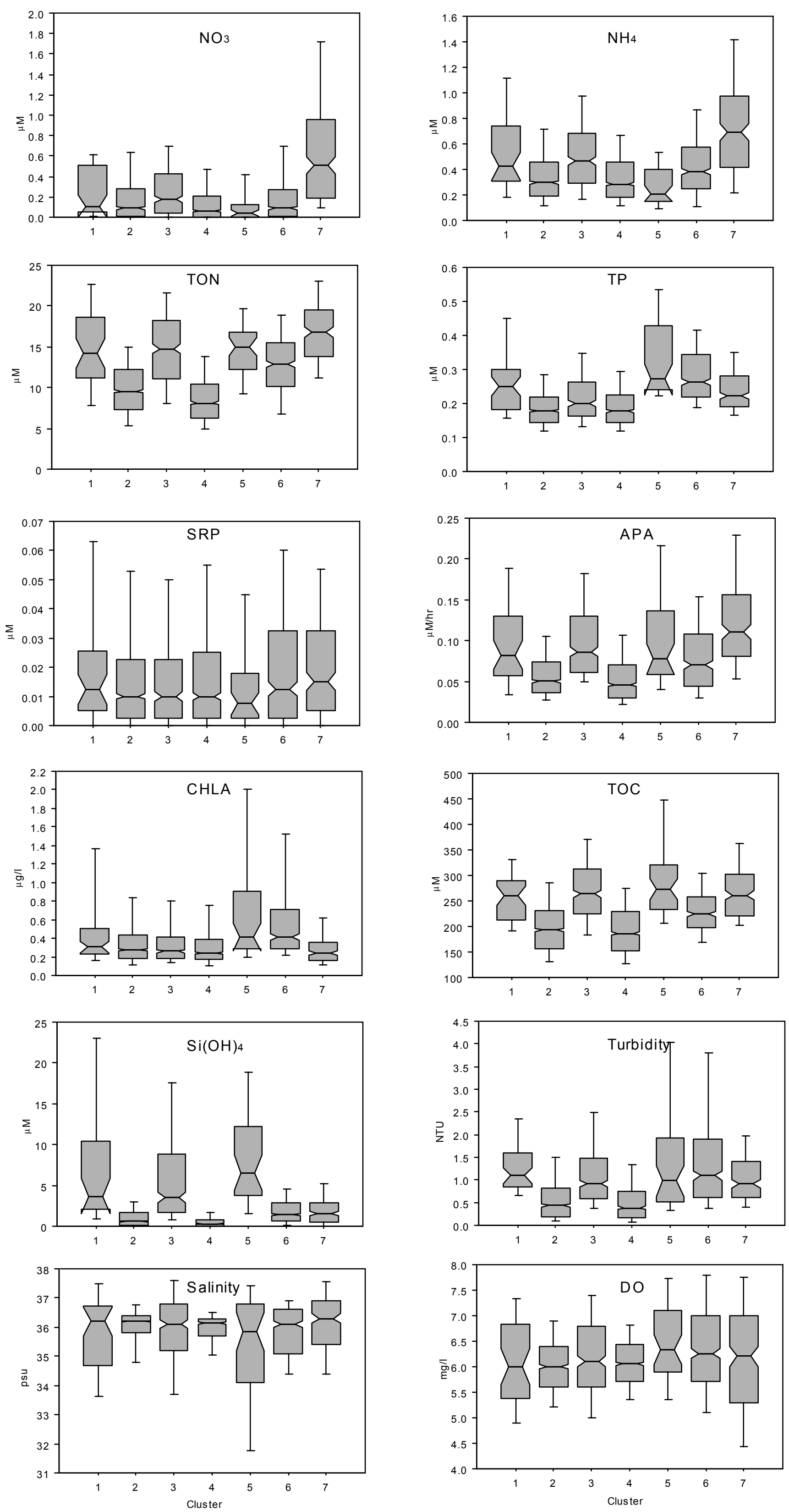

NO3
NH4
TON
TP
SRP
APA
CHLA
TOC
Si(OH)4
Turbidity
Salinity
DO
µM
µM/hr
µg/l
NTU
psu
mg/l
Cluster

Figure 19.

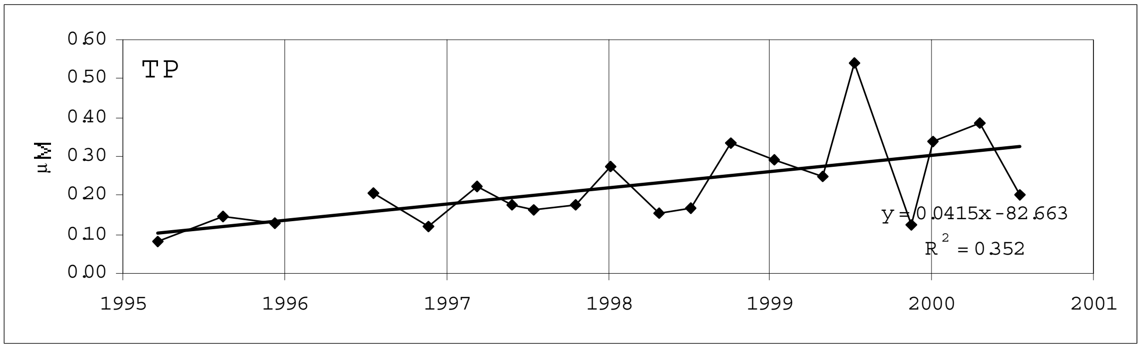


Figure 20.

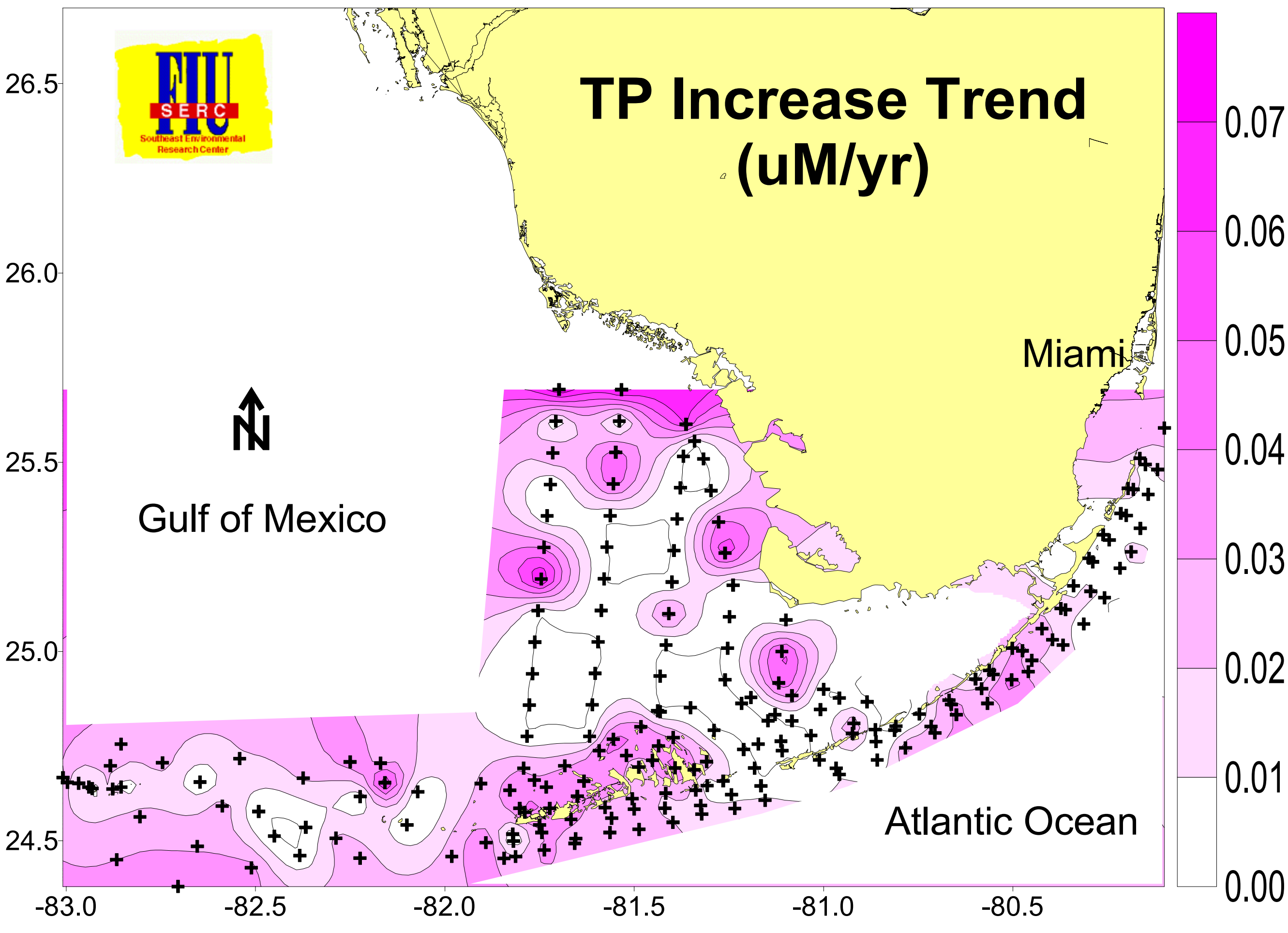


Figure 21.

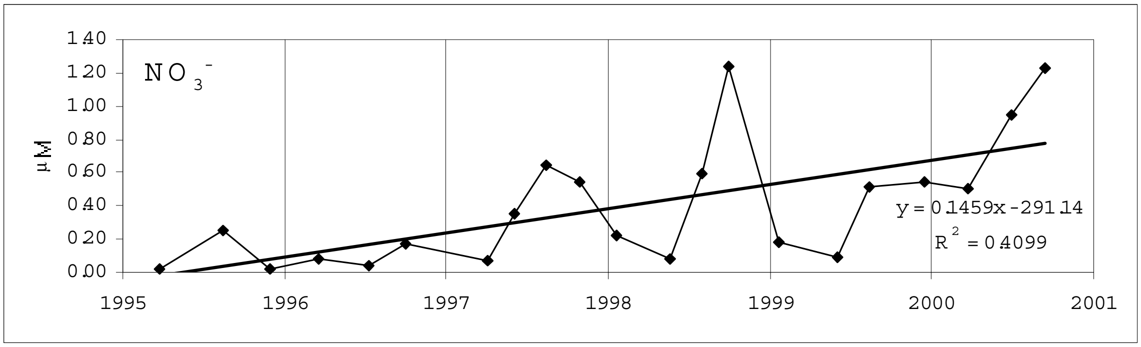


Figure 22.

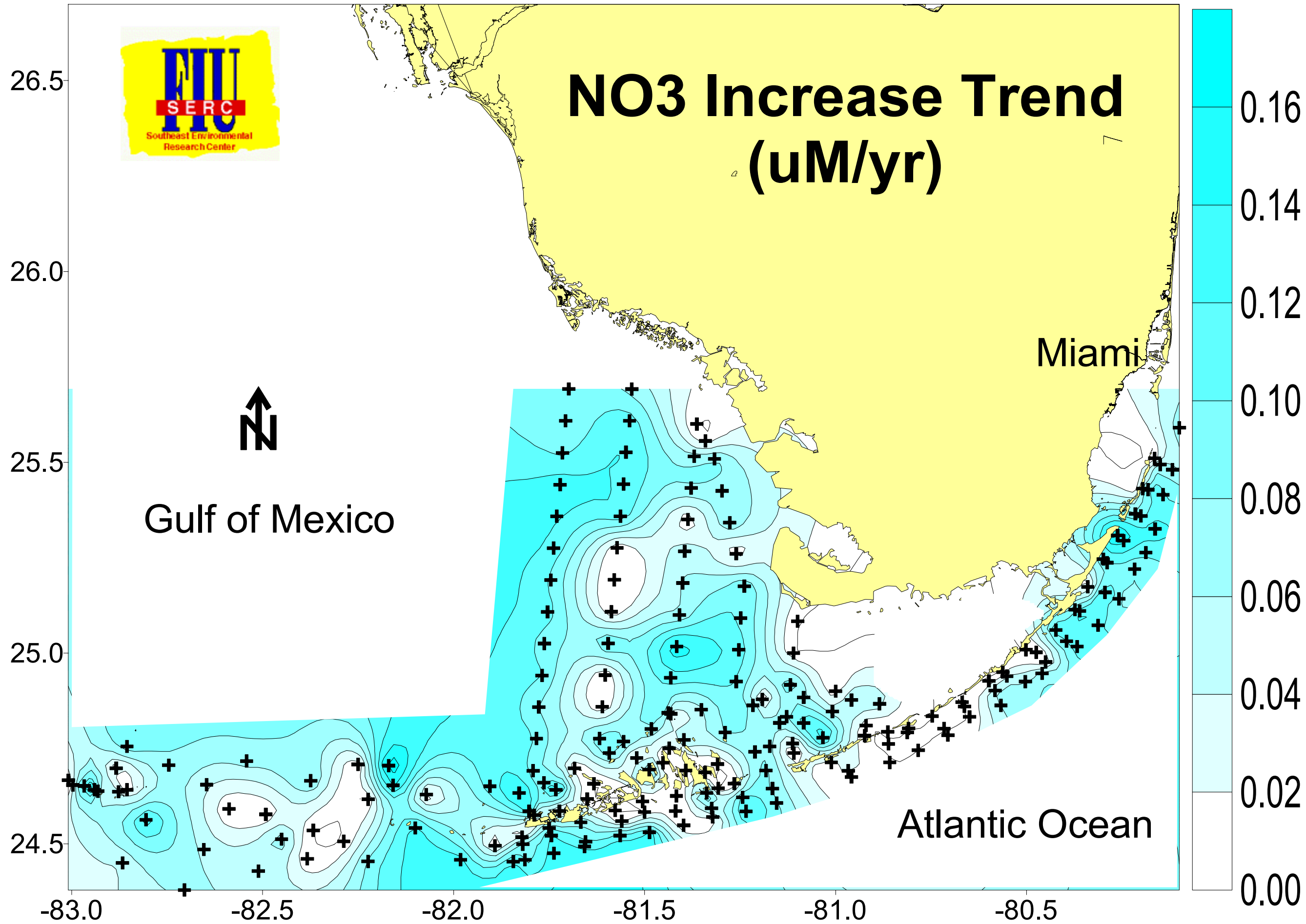


Figure 23.

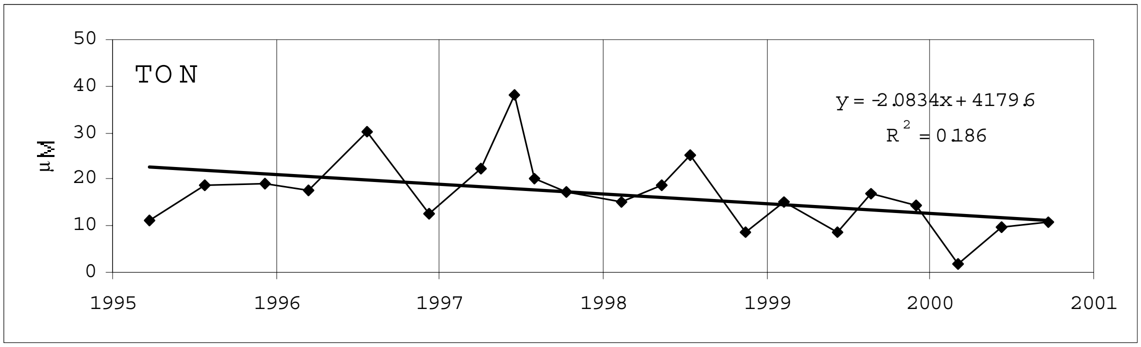


Figure 24.

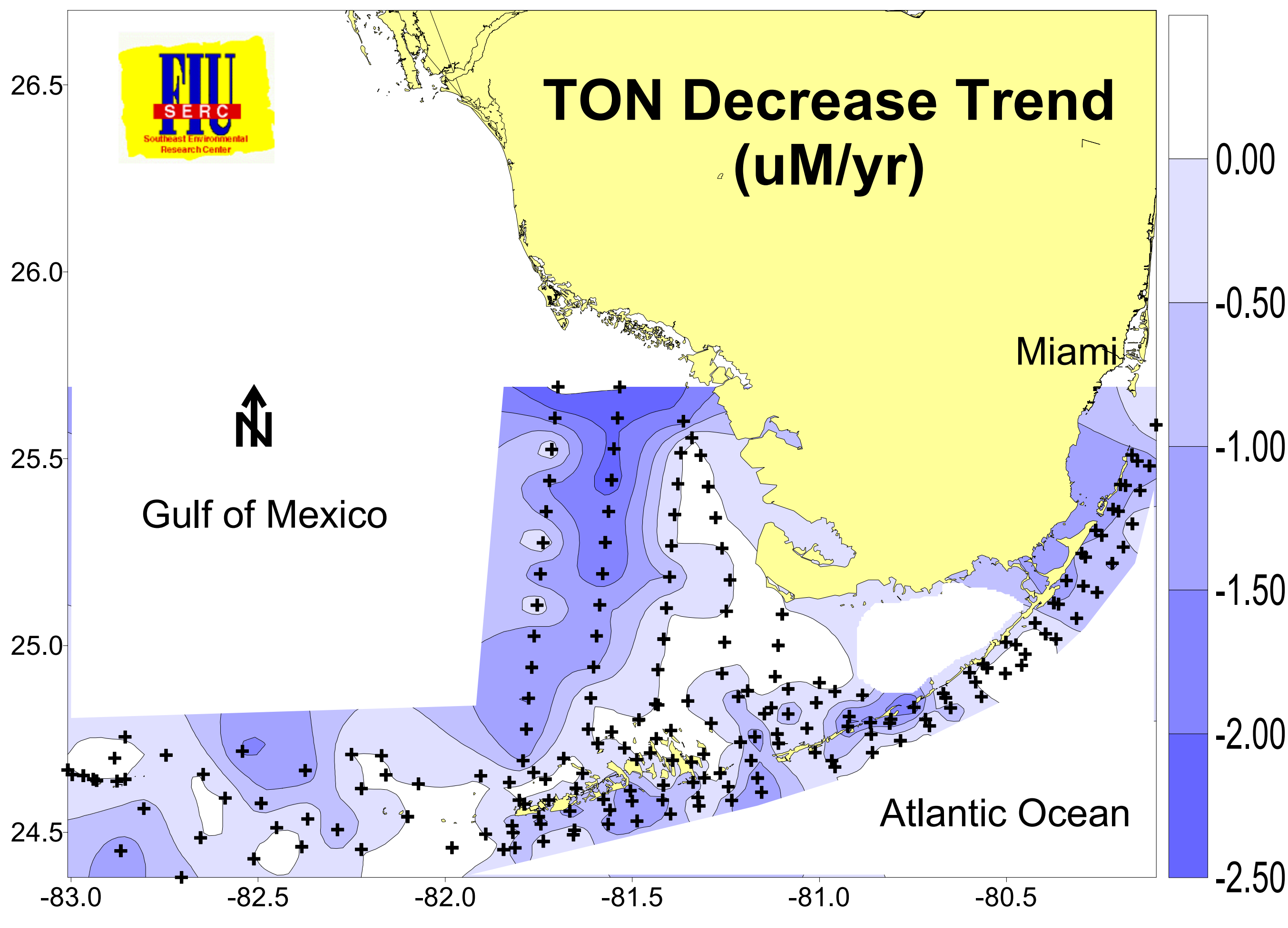
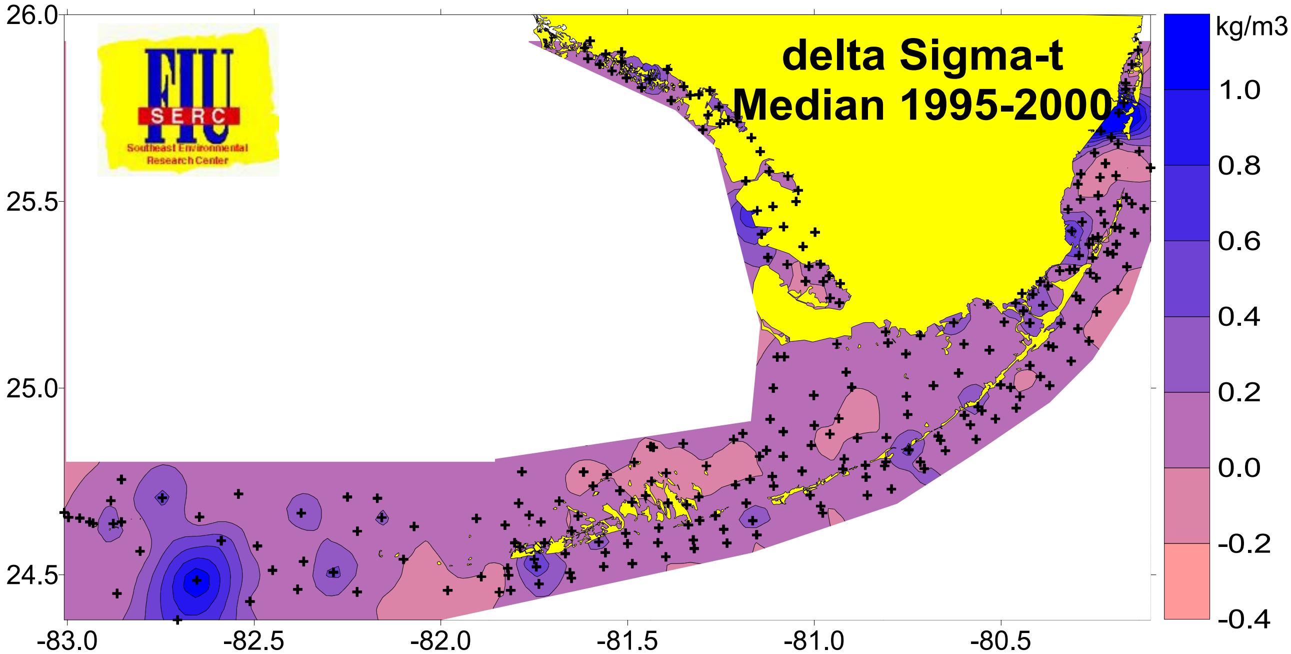


Figure 25.



delta Sigma-t
Median 1995-2000
kg/m3
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
26.0
25.5
25.0
24.5
-83.0
-82.5
-82.0
-81.5
-81.0
-80.5
FIU
SERC
Southeast Environmental Research Center

Figure 26.

List of Appendices

Appendix 1. Color contour maps of selected water quality variables by sampling event. These maps encompass all 354 stations of the SERC Water Quality Monitoring Network which includes the FKNMS, Biscayne Bay, Florida Bay, Whitewater Bay, Ten Thousand Islands, and Southwest Florida Shelf. The data was collected over a period of a month so care should be taken in interpreting these maps as they are not truly synoptic. See serc.fiu/wqmnetwork for updates.