

THE SOUTH FLORIDA ESTUARINE WATER QUALITY MONITORING NETWORK

1997 Cumulative Report

Part 1- Data Synthesis and Discussion

Prepared by:

Ronald D. Jones, Ph.D.
Joseph N. Boyer, Ph.D.
Nancy Black, M.S.

Southeast Environmental Research Program
Florida International University
Miami, FL 33199
<http://www.fiu.edu/~serp>

SFWMD/NPS Cooperative Agreement C-7919.
NPS/SERP Cooperative Agreement 5280-2-9017

THE SOUTH FLORIDA ESTUARINE WATER QUALITY MONITORING NETWORK

FLORIDA BAY
WHITEWATER BAY
TEN THOUSAND ISLANDS
BISCAYNE BAY
SOUTHWEST FLORIDA SHELF

1997 Cumulative Report for

Everglades National Park
and
South Florida Water Management District

Part II - Data Synthesis and Discussion

Southeast Environmental Research Program

Florida International University

Winter, FL 33199

<http://www.fiu.edu/~seep>

EXECUTIVE SUMMARY

One of the primary purposes for conducting long-term monitoring projects is to be able to detect trends in the measured parameters over time. These programs are usually initiated as a response to public perception (and possibly some scientific data) that "the river-bay-prairie-forest-etc. is dying". In the case of Florida Bay, the major impetus was the combination of a seagrass die-off, increased phytoplankton abundance, sponge mortality, and a perceived decline in fisheries beginning in 1987. In response to these phenomena, a network of water quality monitoring stations was established in 1989 to explicate both spatial patterns and temporal trends in water quality in an effort to elucidate mechanisms behind the recent ecological change.

This report summarizes the existing data from the South Florida Estuarine Water Quality Monitoring Network. This includes water quality data collected 28 stations in Florida Bay, 22 stations in Whitewater Bay, 25 stations in Ten Thousand Islands, 25 stations in Biscayne Bay, and 49 stations on the Southwest Florida Shelf (Shelf). Each of the stations in Florida Bay were monitored on a monthly basis with monitoring beginning in March 1991 at stations 1 through 24. (Except monitoring began at stations 14, 19, 22, and 23 in April 1991). In July 1992, stations 25 through 28 were added in Florida Bay. Monthly sampling of stations 29 through 50 in Whitewater Bay were added to the monitoring program in September 1992. Biscayne Bay monthly monitoring began September 1993 for stations 100-125. In May 1996 an analysis of the data was performed to address the adequacy of spatial coverage. At that time, 10 station locations in the Biscayne Bay monitoring network were moved to provide coverage of North Biscayne Bay. The Shelf was sampled quarterly beginning in spring 1995.

We have begun the systematic analysis and interpretation starting with the most extensive dataset: Florida Bay. We have analyzed the data for spatial trends, temporal trends, and for freshwater loading effects. Spatial trend analysis can be performed on data of relatively short period of record (POR); however, time series analysis requires a minimum 5 year POR before significant trends can be recognized over the background noise of interannual variability. Therefore, the type of analysis performed on each estuary is determined by the length of POR.

Trend analysis is an ongoing process; ecosystems change with climate and management strategy, therefore, analytical results may change as more data is collected. It is also important to understand that trend analysis alone will not necessarily provide cause and effect relationships. One of the purposes of any monitoring program should be to use the data gained by routine sampling to extend our understanding of the system by developing new hypotheses as to the underlying processes which drive it. Much inference into the behavior of South Florida estuaries can be made from the observed magnitude and distribution of water quality parameters. This type of multivariate approach should prove useful to scientists and managers faced with the task of interpreting large water quality datasets.

FLORIDA BAY

Spatial Analysis

Previous analyses of Florida Bay water quality has shown that Florida Bay is a phosphorus limited marine ecosystem with a tendency towards hypersalinity. A spatial analysis of 6 years

of data from our monitoring program resulted in the delineation of 3 subsets of our monitoring stations which have robust similarities in water quality. We have argued that these spatially contiguous groups of stations are the result of similar loading and processing of materials, hence we call these groups zones of similar influence (ZSI). The Eastern Bay ZSI acts most like a "conventional" estuary in that it has a quasi-longitudinal salinity gradient caused by the interaction of clearly definable seawater and freshwater endmembers. In contrast, the Central Bay is a hydrologically isolated area with low and infrequent terrestrial freshwater input, long water residence time, and high evaporative potential. The Western Bay ZSI is the most tidally influenced by the Gulf of Mexico and is also most isolated from direct overland freshwater sources.

The general view of Florida Bay that emerges from this analysis is that of an ecosystem dominated by its restricted hydrology. The shallow banks inhibit water movement within the estuary which results in spatial heterogeneity in water quality. Mixing of freshwater occurs from a northeast-southwest direction. Input of Shelf water occurs via the Western Bay and is slowly transported to the northeast into the Central Bay where, depending upon rainfall, it is either entrained by the flow of water out of Florida Bay or evaporated resulting in hypersaline conditions. In contrast, the mangrove forests of Whitewater Bay possess a well developed channel system which culminates in a series of river dominated estuaries. Tidal range and exchange is much greater in this area and results in obvious differences in salinity and nutrient distributions.

Many of the measured parameters had seasonal maxima in the summer rainy season. Obviously, water temperature followed a predictable pattern, with warmer temperatures in summer months, but concentrations of TON and TOC also tended to be greatest in the summer. This may be a result of enhanced decomposition of particulate organic matter in the warmer months or simply the concentration of solute by evaporation (salinity was also higher in the summer). Because of the lack of seasonality of TP and the fact that TON is the major component of TN, TN:TP ratios were also highest in the summer. Indicators of biomass and activity of the phytoplankton, Chl *a* and APA, tended to have maxima in the fall.

Temporal Analysis

In contrast, some parameters were highest in the winter dry season, such as the TIN pool, turbidity, and DO_{sat}. It is unclear as to what drives this pattern in TIN but it is not due increased allochthonous loading from streamflow as this is the dry season. It is possible that the lower summer/fall concentrations are due to uptake by phytoplankton or it may be due to benthic remineralization as a result of seagrass senescence. Winds during this period are higher than the rest of the year and generally come from the northeast. Higher winds and the long fetch from this direction may result in more resuspension of the fine muds from the bottom of Florida Bay. The DO_{sat} maxima in winter and spring may be due to increased diffusion of oxygen across the air-water interface in the more turbulent and windy seasons, as well as there being less respiratory consumption of oxygen in the cooler months.

After removing the seasonal signal from the time series of water quality data, many aspects of water quality displayed directional change over the period of record of this data set. Three parameters displayed the same long-term trend in all three ZSI: salinity, TP and SRP. Salinity

declined in all sections of Florida Bay as a function of variations in climate: the beginning of our data collection coincided with the ending of a regional drought, and the years 1994-96 have all been wetter than normal, but no statistically significant trend was evident. Fresh water enters Florida Bay as rainfall, surface water runoff and groundwater; more rainfall has led to a general increase in the surface water inputs since 1987. Regression of detrended monthly precipitation and combined monthly flows (S18C + Taylor Slough) was significant but explained <2% of the variance, supplying very little predictive power for any type of modeling effort. Full scale prediction of salinities in Florida Bay will require a more detailed assessment of inputs and mixing across Florida Bay

Freshwater entering Florida Bay from overland sources has a lower TP concentration than seawater entering Florida Bay from the Gulf of Mexico and from precipitation. This may help to explain some of the decline in P concentrations in the Bay but without process rate measurements we can only speculate as to the cause. Other water quality parameters had different long-term trends in the different zones (e.g. Chl *a*). These regional differences are the result of the varying importance of freshwater runoff, oceanic exchange, and internal processing of nutrients across Florida Bay and are discussed below.

Nutrient Loading Analysis

Freshwater flows to the Eastern Florida Bay via Taylor Slough (S175 & S332) and the coastal basin (S18C) fluctuated widely during 1984-96 and were not significantly related to precipitation. However, after 1990, a seven-fold increase in freshwater input was observed. At the same time, the contribution of the S332 to the total flow increased from 47-256 Mm³ yr⁻¹ (17-32%). We believe part of this effect was due to a management strategy of increased pumping at the S332 and that these management efforts were effective in increasing water to the Taylor Slough. Average annual salinity in Eastern Florida Bay during 1989-96 declined by 18 ppt and was significantly related to increased flow ($r^2=0.75$) but not to precipitation. TP loading ranged from 0.9-7.7 metric tons yr⁻¹ and was significantly related to flow ($r^2=0.82$) with the average concentration being 0.32 μ M (10 ppb). While TP loading increased, ambient TP concentration in Eastern Florida Bay decreased from 0.4 to 0.2 μ M. TN loading ranged from 98.7-635 metric tons yr⁻¹ and was also highly correlated with flow ($r^2=0.92$). Average input TN concentration was 62 μ M while ambient TN concentration in Eastern Florida Bay averaged 55 μ M. Ambient TN:TP ratios in Eastern Florida Bay were maintained at or near the high input TN:TP ratios (mean=224), implying that both the input ecosystem (Everglades) and the receiving waters are P limited. There was no relationship between either TP or TN loading and Chl *a* in Eastern Florida Bay; instead, there was a significant regression with ambient TP concentration ($r^2=0.75$). This indicates that phytoplankton are responding to internally cycled P and not to external loading.

For an estuary to exhibit increased P loading while P concentration declines usually requires an increase in either storage or advection. Chl *a* concentrations decreased in Eastern Florida Bay, indicating that phytoplankton uptake did not account for the decline in P in this zone. An increase in seagrass cover or greater binding to sediments with decreased salinity could possibly account for this decline but has not been quantified. We believe the answer lies in the fact that the TP concentration of the incoming freshwater is approximately equal to ambient TP concentrations in the Bay. We propose that management activities to increase input of

freshwater from Taylor Slough and the coastal basin may have effected a significant decline in both salinity and TP concentrations in Eastern Florida Bay via simple dilution.

All the above results point to the simple conclusion that Florida Bay is not like other estuaries of the eastern USA. Many people continue to believe the dogma that Florida Bay is a eutrophic ecosystem polluted by nutrient runoff from agriculture. Were it not for the Everglades marshes, this might indeed be true. We have shown that the actuality is one in which the loading inputs of the limiting nutrient, P, are at or below the ambient concentrations of the Eastern Bay itself. Therefore, nutrient loading reported in metric tons yr^{-1} is misleading because, in this case, it is the input concentration that makes the most difference.

Whitewater Bay - Ten Thousand Islands Complex

Spatial Analysis

Using the above approach the TTI-WWB complex was partitioned into 6 distinct zones having similar water quality. The first cluster was composed of 13 stations in and around the Shark, Harney, Broad, and Lostmans Rivers and is called the "Mangrove River" group. This cluster also included a sampling station just off the Faka Union Canal. The second cluster was made up of the 8 stations enclosed within Whitewater Bay proper (called "Whitewater Bay"). Twelve stations situated mostly in and around the coastal islands of TTI-WWB formed the "Gulf Island" group. The water quality characteristics at the Coot Bay site were sufficiently different so as to be a cluster of its own. The next cluster contained the northernmost 2 stations in the Blackwater River estuary ("Blackwater"). Finally, the "Inland Waterway" ZSI included 11 stations distributed throughout the inside passage as well as the Chatham River and the station off Everglades City.

Marked differences in physical, chemical, and biological characteristics among zones were illustrated by this technique. The general spatial trend is one of relatively high APA, TON, and TOC in the south declining northward along the coast while salinity, turbidity, TP, and SRP increase. The net effect is the formation of a gradient with strong phosphorus limitation occurring in the southern region shifting to a more balanced TN:TP ratio in the northern area around the Blackwater River. Further analysis of this relationship is planned.

Biscayne Bay

Preliminary Spatial Analysis

Biscayne Bay was partitioned into 6 distinct ZSI using the above statistical analysis. The first cluster was composed of 2 stations closest to the shore in the south Bay; they were called the "Alongshore" group. The second cluster was made up of the 5 stations farther from the coast called "Inshore". Thirteen stations situated mostly in the bay proper were called the "Main Bay" group. The next cluster contained the 3 stations situated in areas of great tidal exchange ("Ocean Channel"). Two stations in Card Sound grouped together "Card Sound". Finally, the "Turkey Point" station comprised its own cluster. As mentioned previously, 10 stations were selected for their status as being either redundant (as in some of the Main Bay stations) or as outliers (Turkey Point and the Ocean Channel sites) and redistributed throughout the Bay to

provide us with more complete coverage. For purposes of this report, the stations moved into the area north of the Rickenbacker Causeway will be defined as a distinct cluster ("North Bay") and discussed below.

It is clear that there is a gradient of increasing salinity with decreasing nutrient concentration with distance from the west coast of the Bay. For Alongshore, Inshore, and Main Bay clusters, highest concentrations of NO_3 , NO_2 , NH_4 , and TP were observed in the Alongshore stations. North Bay showed NH_4 levels comparable to the high concentrations seen Alongshore but had a higher median salinity. In addition, North Bay had the highest median TP concentration of any ZSI. Card Sound had relatively high NH_4 concentration relative to the other nutrients. Some of this may be attributed to the long water residence time of this basin as evidence by near ocean salinities. APA as well as TON and TOC concentrations were highest in Alongshore > Inshore > Main Bay, denoting a freshwater source. It is interesting to note the northwards decreasing gradient of TON and TOC along the coast. Concentrations of SRP were so low so as to be undetectable in many instances. The relationship between SRP and Chl *a* was very weak and may have been influenced by other factors yet determined. This is a preliminary analysis and will be repeated after a few more years of data have been collected.

Southwest Florida Shelf

Preliminary Spatial Analysis

The above statistical analysis objectively classified the 49 sampling sites into 3 zones having similar water quality. The first cluster was composed of 2 stations closest to the shore off Cape Sable; they were called the "Sable" group. The second cluster was made up of the 7 more northerly stations nearest the coast and called "Shark" after the Shark Slough, the main source of freshwater to the region. The remaining stations were called the "Shelf" group.

It is clear that the Sable stations have much higher concentrations of NO_3 , NO_2 , NH_4 , and SRP while the Shark and Shelf stations were similar. In addition, there is a decreasing concentration gradient of Sable>Shark>Shelf for TP, Chl *a* and turbidity. Finally, the inverse relationship between salinity and SiO_2 is evident for all ZSI. The source of SiO_2 in this area of carbonate sediments is from silicate sands and siliceous periphyton (diatoms) found in the Shark River Slough watershed. SiO_2 can therefore be used as a freshwater tracer in this system.

Although these analyses are very preliminary (only 10 sampling events) it is possible to speculate that the clusters are formed as a function of hydrology and circulation patterns. We believe that the Sable stations clearly show the input of freshwater from Shark Slough being transported south and east around the Cape. Water overlying the Shark stations probably originates somewhere north of the Ten Thousand Islands. Our level of resolution is very low due to the limited numbers of sampling events and by the relatively large spatial gap between coastal and Shelf sampling sites. A better understanding of local circulation patterns in addition to increased density and frequency of sampling in the nearshore region may help define the coupling between freshwater inflow and Shelf water quality. This is a preliminary analysis and will be repeated after a few more years of data have been collected.

ACKNOWLEDGMENTS

We thank all the field and laboratory technicians involved with this project including: Jeff Absten, Omar Beceiro, Sylvia Bolanos, Tom Frankovich, Bill Gilhooly, Scott Kaczynski, Elaine Kotler, Cristina Menendez, Jennifer Mohammed, Susy Perez, Pierre Sterling, and especially Pete Lorenzo. This project was possible due to the continued funding of the South Florida Water Management District through the Everglades National Park (SFWMD/NPS Cooperative Agreement C-7919 and NPS/SERP Cooperative Agreement 5280-2-9017).

This report is contribution #66 of the Southeast Environmental Research Program at Florida International University.

TABLE OF CONTENTS

Part 1 - Data Synthesis and Discussion

INTRODUCTION AND PROJECT DESCRIPTION

FLORIDA BAY

- Station Map
- Spatial Analysis
- Temporal Analysis
- Nutrient Loading Analysis

WHITEWATER BAY - TEN THOUSAND ISLANDS COMPLEX

- Station Map
- Spatial Analysis

BISCAYNE BAY

- Station Map
- Preliminary Spatial Analysis

SOUTHWEST FLORIDA SHELF

- Station Map
- Preliminary Spatial Analysis

Part 2 - Appendices

APPENDIX 1: Florida Bay - Whitewater Bay Data Summary

APPENDIX 2: Biscayne Bay Data Summary

APPENDIX 3: Ten Thousand Islands Data Summary

APPENDIX 4: Southwest Florida Shelf Data Summary

INTRODUCTION AND PROJECT DESCRIPTION

Project Background

This report includes water quality data collected monthly from 28 stations in Florida Bay, 22 stations in Whitewater Bay, 25 stations in Ten Thousand Islands, and 25 stations in Biscayne Bay. A total of 49 stations on the SW Shelf were collected on a quarterly basis. Figure 1 shows the location of all the fixed sampling stations.

Each of the stations in Florida Bay were monitored on a monthly basis with monitoring beginning in March 1991 at stations 1 through 24. (Except monitoring began at stations 14, 19, 22, and 23 in April 1991). In July 1992, stations 25 through 28 were added in Florida Bay. Monthly sampling of stations 29 through 50 in Whitewater Bay were added to the monitoring program in September 1992. Biscayne Bay monthly monitoring began September 1993 for stations 100-125. In May 1996 an analysis of the data was performed to address the adequacy of spatial coverage. At that time, 10 station locations in the Biscayne Bay monitoring network were moved to provide coverage of North Biscayne Bay. The Southwest Florida Shelf was sampled quarterly beginning in spring 1995.

Analytical Methods

Surface salinity (ppt) and temperature ($^{\circ}\text{C}$) were measured using a combination salinity-conductivity-temperature probe (Orion model 140). Dissolved oxygen (DO , mg l^{-1}) was measured 10 cm below the surface using an oxygen electrode (Orion model 840) corrected for salinity and temperature.

Duplicate, unfiltered water samples were collected from 10 cm below the surface using acetone-washed and sample rinsed 120 ml HDPE bottles and kept at ambient temperature in the dark during transport. Duplicate water samples for dissolved nutrient analysis were collected using acid-washed and sample rinsed 150 ml syringes. Samples were filtered (25 mm glass fiber GF/F) by hand into acetone-washed and sample rinsed 60 ml HDPE bottles, which were capped and immediately placed on ice in the dark for transport. The wet filters, used for chlorophyll *a* (Chl *a*) analysis, were placed in 1.8 ml plastic centrifuge tubes to which 1.5 ml of 90% acetone was added (Strickland and Parsons 1972); they were then capped and put into a dark bottle on ice for transport.

Unfiltered water samples were analyzed for total organic carbon (TOC), total nitrogen (TN), total phosphorus (TP), 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 $\text{pH} < 2$ and purging with CO_2 -free air. TN was measured using an ANTEK 7000N Nitrogen Analyzer using O_2 as carrier gas instead of argon to promote complete recovery of the nitrogen in the water samples (Jones and Frankovich in press). TP was determined using a dry ashing, acid hydrolysis technique (Solórzano and Sharp 1980). The APA assay measures the activity of alkaline phosphatase, an enzyme used by bacteria to mineralize phosphate from organic compounds. The assay is performed by adding a known concentration of an organic phosphate compound (o-methylfluorescein phosphate) to an unfiltered water sample. Alkaline phosphatase in the water sample cleaves the phosphate, leaving o-methylfluorescein, a highly fluorescent

compound. The fluorescence of initial and 2 hr incubations were measured using a Gilford Fluoro IV spectrofluorometer (excitation = 430 nm, emission = 507 nm) and subtracted to give APA ($\mu\text{M h}^{-1}$). 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 ammonium (NH_4) on a four channel autoanalyzer (Alpkem model RFA 300). Filters for Chl a content ($\mu\text{g l}^{-1}$) 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) and compared to a standard curve of pure Chl a (Sigma).

Some parameters were not measured directly, but were calculated by difference. Nitrate (NO_3) was calculated as $\text{NO}_x - \text{NO}_2$. Total inorganic nitrogen (TIN) was calculated as $\text{NO}_x + \text{NH}_4$. Total organic nitrogen (TON) was defined as $\text{TN} - \text{TIN}$. Concentrations for each of these parameters are reported in this report in units of milligrams per liter (mg l^{-1}) or the equivalent parts per million (ppm), except where noted. All nutrient concentrations are based on the atomic weight of primary nutrient species (ppm-N, ppm-P, and ppm-C), not the molecular weight. Be aware that some previous data provided to Everglades National Park may be in micro-moles per liter (μM). All N:P ratios discussed are calculated on a mole:mole basis.

FLORIDA BAY Map

Table 1: Florida Bay/Whitewater Bay Station Summary

Station Name	Station Number	Zone	Latitude	Longitude	Period of Record	Surveys
Card Sound Bridge	1	FBE	25 16.413	80 22.475	March 91 - Dec 97	1-82
Middle Bay	2	FBE	25 17.102	80 23.702	March 91 - Dec 97	1-82
Manatee Bay	3	FBE	25 15.062	80 24.910	March 91 - Dec 97	1-82
Barnes Sound	4	FBE	25 13.304	80 23.299	March 91 - Dec 97	1-82
Blackwater Sound	5	FBE	25 10.443	80 25.385	March 91 - Dec 97	1-82
Little Blackwater Sound	6	FBE	25 12.401	80 26.424	March 91 - Dec 97	1-82
Highway Creek	7	FB7	25 15.216	80 26.649	March 91 - Dec 97	1-82
Long Sound	8	FBE	25 13.642	80 27.700	March 91 - Dec 97	1-82
Duck Key	9	FBE	25 10.624	80 29.494	March 91 - Dec 97	1-82
Joe Bay	10	FBE	25 13.468	80 32.195	March 91 - Dec 97	1-82
Little Madeira Bay	11	FBE	25 10.510	80 37.615	March 91 - Dec 97	1-82
Terrapin Bay	12	FBC	25 08.422	80 42.967	March 91 - Dec 97	1-82
Whipray Basin	13	FBC	25 05.485	80 45.287	March 91 - Dec 97	1-82
Garfield Bight	14	FBC	25 09.029	80 48.553	April 91 - Dec 97	2-82
Rankin Lake	15	FBC	25 07.283	80 48.173	March 91 - Dec 97	1-82
Murray Key	16	FBW	25 07.096	80 56.379	March 91 - Dec 97	1-82
Johnson Key Basin	17	FBW	25 02.548	80 54.889	March 91 - Dec 97	1-82
Rabbit Key Basin	18	FBW	25 00.145	80 54.006	March 91 - Dec 97	1-82
Twin Key Basin	19	FBE	24 58.660	80 45.211	April 91 - Dec 97	2-82
Peterson Key	20	FBE	24 55.770	80 45.028	March 91 - Dec 97	1-82
Porpoise Lake	21	FBE	25 00.396	80 40.876	March 91 - Dec 97	1-82
Captain's Key	22	FBE	25 02.405	80 36.843	April 91 - Dec 97	2-82
Park Key	23	FBE	25 07.078	80 35.983	April 91 - Dec 97	2-82
Butternut Key	24	FBE	25 06.105	80 31.884	March 91 - Dec 97	1-82
East Cape	25	FBW	25 05.022	81 04.835	July 92 - Dec 97	17-82
Oxfoot Bank	26	FBW	24 58.844	81 00.098	July 92 - Dec 97	17-82
Sprigger Bank	27	FBW	24 55.116	80 56.092	July 92 - Dec 97	17-82
Old Dan Bank	28	FBE	24 52.032	80 48.429	July 92 - Dec 97	17-82
First Bay	29	MR	25 33.272	81 11.020	Sept 92 - Dec 97	19-82
Third Bay	30	MR	25 34.810	81 07.256	Sept 92 - Dec 97	19-82
Big Lostman's Bay	31	MR	25 34.055	81 04.288	Sept 92 - Dec 97	19-82
Cabbage Island	32	MR	25 31.764	81 02.603	Sept 92 - Dec 97	19-82
Broad River Bay	33	MR	25 29.984	81 02.939	Sept 92 - Dec 97	19-82
Middle Broad River	34	MR	25 29.163	81 06.669	Sept 92 - Dec 97	19-82
Mouth Broad River	35	MR	25 28.501	81 09.176	Sept 92 - Dec 97	19-82
South Mouth Harney River	36	MR	25 24.701	81 08.487	Sept 92 - Dec 97	19-82
Harney River Junction	37	MR	25 25.901	81 04.943	Sept 92 - Dec 97	19-82
Tarpon Bay	38	MR	25 25.037	80 59.906	Sept 92 - Dec 97	19-82
Gunboat Island	39	MR	25 22.735	81 01.844	Sept 92 - Dec 97	19-82
Ponce De Leon Bay	40	GI	25 20.983	81 07.474	Sept 92 - Dec 97	19-82
Oyster Bay	41	GI	25 19.869	81 04.360	Sept 92 - Dec 97	19-82
North of Marker 36	42	WB	25 19.560	81 00.873	Sept 92 - Dec 97	19-82
West of Marker 34	43	WB	25 17.168	81 01.419	Sept 92 - Dec 97	19-82
Watson River Chickee	44	WB	25 19.912	80 59.022	Sept 92 - Dec 97	19-82
Mouth North River	45	WB	25 18.054	80 57.620	Sept 92 - Dec 97	19-82
Midway Keys	46	WB	25 17.102	80 58.548	Sept 92 - Dec 97	19-82
Mouth of Roberts River	47	WB	25 16.779	80 55.846	Sept 92 - Dec 97	19-82
West of Marker 18	48	WB	25 14.448	80 57.476	Sept 92 - Dec 97	19-82
Southeast of Marker 12	49	WB	25 13.704	80 55.980	Sept 92 - Dec 97	19-82
Coot Bay	50	COOT	25 11.452	80 54.848	Sept 92 - Dec 97	19-82

Spatial Characterization of Water Quality in Florida Bay and Whitewater Bay by Multivariate Analyses: Zones of Similar Influence

JOSEPH N. BOYER¹

*Southeast Environmental Research Program
Florida International University
Miami, Florida 33199*

JAMES W. FOURQUREAN

RONALD D. JONES

*Southeast Environmental Research Program and
Department of Biological Sciences
Florida International University
Miami, Florida 33199*

ABSTRACT: We apply an objective statistical analysis to a 6-yr, multiparameter dataset in an effort to describe the spatial dependence and inherent variation of water quality patterns in the Florida Bay-Whitewater Bay area. Principal component analysis of 16 water quality parameters collected monthly over a 6-yr period resulted in five principal components (PC) that explained 71.8% of the variance of the original variables. The "organic" component (PC_I) was composed of TN, TON, APA, and TOC; the "inorganic N" component (PC_{II}) contained NO₂⁻, NO₃⁻, and NH₄⁺; the "phytoplankton" component (PC_{III}) was made up of turbidity, TP, and Chl *a*; DO and temperature were inversely related (PC_{IV}); and salinity was the only parameter included in PC_V. A cluster analysis of mean and SD of PC scores resulted in the spatial aggregation of 50 fixed monitoring stations in Florida Bay and Whitewater Bay into six zones of similar influence (ZSI) defined as Eastern Florida Bay, Core Florida Bay, Western Florida Bay, Coot Bay, the Inner Mangrove Fringe, and the Outer Mangrove Fringe. Marked differences in physical, chemical, and biological characteristics among ZSI were illustrated by this technique. Comparison of medians and variability of parameter values among ZSI allowed large-scale generalizations as to underlying differences in water quality in these regions. For example, Eastern Florida Bay had lower salinity, TON, TOC, TP, and Chl *a* than the Core Bay as a function of differences in freshwater inputs and water residence time. Comparison of medians and variability within ZSI resulted in new hypotheses as to the processes generating these internal patterns. For example, the Core Bay had very high TON, TOC, and NH₄⁺ concentrations but very low NO₃⁻, leading us to postulate the inhibition of nitrification via CO production by TOC photolysis. We believe that this simple, objective approach to spatial analysis of fixed-station monitoring datasets will aid scientists and managers in the interpretation of factors underlying the observed parameter distribution patterns. We also expect that this approach will be useful in focussing attention on specific spatial areas of concern and in generating new ideas for hypothesis testing.

Introduction

Florida Bay and the mangrove estuaries of the Whitewater Bay area in South Florida act as the marine receiving-end of the Everglades, one of the largest wetland ecosystems in the world. Recent ecological changes in this region have brought attention to the sensitivity of the ecosystem to disturbance. A list of these disturbances and impacts includes the invasion of exotic species in the freshwater wetlands and uplands (Bodle et al. 1994), periods of prolonged hypersalinity of coastal em-

bayments (Fourqurean et al. 1993), a poorly understood seagrass die-off (Robblee et al. 1991), sponge mortality events (Butler et al. 1995), and elevated phytoplankton abundance (Phlips and Badylak 1996). In response to these early warning signs, a network of water quality monitoring stations was established in 1989 so that trends in water quality could be addressed.

Primary productivity of both the water column (Fourqurean et al. 1993; Phlips and Badylak 1996) and the benthos (Powell et al. 1989; Fourqurean et al. 1992a, 1992b) of Florida Bay is limited by phosphorus availability. Recent increases in the abundance of phytoplankton (Phlips and Badylak 1996) indicate that P availability has increased in

¹ Corresponding Author; tele: 305-348-4076 (Office); fax: 305-348-4096; boyerj@servax.fiu.edu.

the water column between 1989 and 1994. Concerns that this increased P availability is due to cultural eutrophication of the system have been raised (Lapointe and Clark 1992). In contrast to Florida Bay, there is almost no water quality data available for the Whitewater Bay mangrove estuaries.

Environmental monitoring programs are essential for our understanding and management of ecosystems. Before one can recognize environmental changes, some idea of baseline variability must be established against which to evaluate gross deviations. Owing to the deleterious effects of man's activities on lakes, estuaries, and coastal oceans, it is vitally important to understand spatial as well as temporal patterns in water quality in these systems in an effort to direct management efforts.

Florida Bay, Whitewater Bay, and the smaller mangrove estuaries of the region are highly compartmentalized by geomorphology, making it difficult to study nutrient biogeochemistry using standard schemes of estuarine ecology. Sources of both fresh water and nutrients are difficult to quantify, owing to the nonpoint source nature of runoff from the Everglades. Thus, one-dimensional mixing diagrams, so useful in river-dominated estuaries of the temperate zone, are inappropriate for studying nutrient behavior in these systems. Despite this, it would be useful to define subsections of the systems of similar nature in order to understand the roles of various nutrient sources, sinks, and processes.

As we were interested in understanding the spatial patterns of water quality of the Florida Bay-Whitewater Bay area, analysis required the reduction of a complicated data matrix into fewer elements. Even a modest water-quality monitoring program can generate a daunting amount of data (~83,000 points, this study). Multivariate statistical techniques can be used to reduce the number of variables into a smaller set of independent, synthetic variables that capture the variance of the original dataset. Objective analysis (*sensu* Jackilee and Hamilton 1977) uses singular decomposition of a matrix to classify oceanographic profile data into areas with similar physical and chemical characteristics. Fourqurean et al. (1993) applied principal component analysis (PCA) to water-quality data from Florida Bay, reducing the number of independent variables from 17 to 3 composite variables which explained >90% of the variance of the original dataset. PCA and clustering algorithms have been used to characterize mesoscale variability of a phytoplankton bloom in the Lower St. Lawrence estuary (Vézina et al. 1995). Most recently, a PCA-clustering method was applied to seasonal measurements of percent cover of 15 macrophyte species and 15 invertebrates at 18 stations in Nar-

ragansett Bay in an effort to identify similarities among stations (Hardin et al. 1996).

To understand the factors influencing nutrient biogeochemistry in embayments in southwestern Florida, it is important to be able to objectively group stations of similar water quality (as physical and chemical parameters). In this paper, we apply PCA to a 6-yr, multiparameter dataset in an effort to describe the spatial dependence and inherent variation of water quality patterns in the Florida Bay-Whitewater Bay area. This is followed by a cluster analysis, which objectively classifies sampling stations in this network into groups with similar water quality for the period of record. Water quality at a specific site is the result of the interaction of a variety of driving forces, including oceanic and freshwater inputs and outputs, sinks, and internal cycling. It is reasonable to assume that contiguous groups of stations with similar water quality are the result of comparable interactions, hence we call these regions zones of similar influence (ZSI). The utility of this approach for further analysis and new hypothesis development are discussed.

Methods

SITE CHARACTERISTICS

Florida Bay is a shallow lagoon located off the southern tip of the Florida peninsula (Fig. 1). It is bounded by the Everglades to the north and is open to the Gulf of Mexico along its western margin. The main line of the Florida Keys, a Pleistocene reef, separates Florida Bay from the Atlantic Ocean. Florida Bay receives freshwater runoff from Taylor Slough in the Everglades as well as the C-111 canal output located in Highway Creek at its most northeast end. The sediments of Florida Bay are composed mostly of biogenic carbonate muds (Bosence 1989) so weathering of pre-existing substratum is not an important source of nutrients. The muddy sediments are colonized by seagrass beds (dominated by *Thalassia testudinum*), which occur over 95% of the bottom of Florida Bay (Zieman et al. 1989). Shallow mud banks divide Florida Bay into relatively discrete basins, restricting water mixing between basins and attenuating both tidal range and current speed.

The Whitewater Bay area is located on the southwestern coast of the Florida peninsula and is composed of mangrove-lined streams and rivers originating from the Shark River Slough in the Everglades. It is a brackish complex that drains into the SW Florida Shelf region of the Gulf of Mexico (hereafter called Shelf). In the region from Cape Romano to Cape Sable, there are over 60,000 ha of mangrove forest; this forest is made up of tall

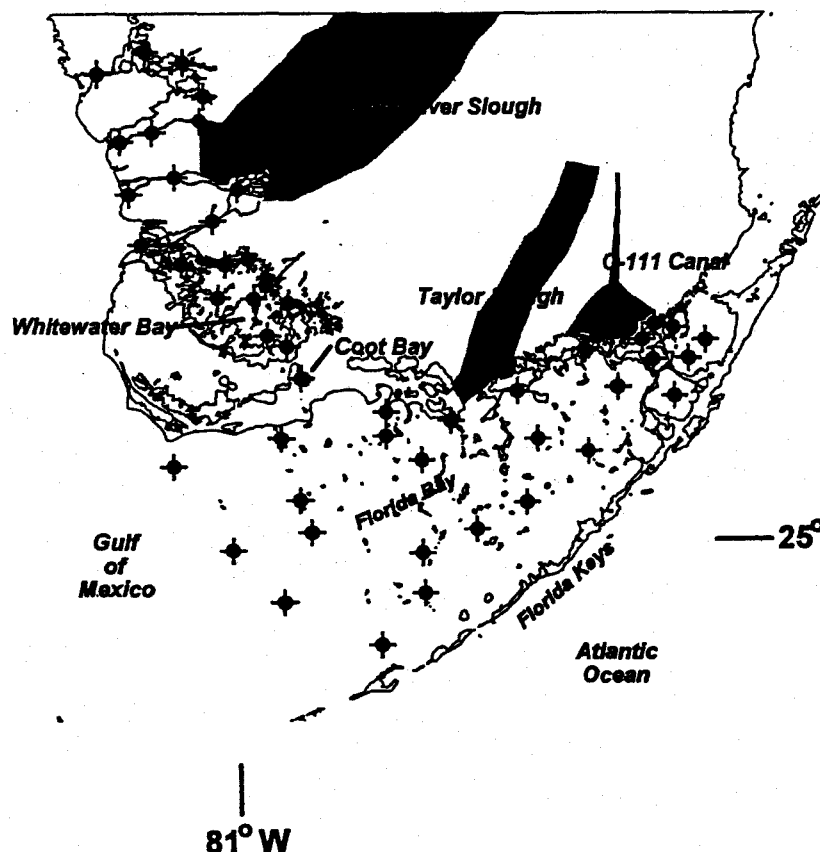


Fig. 1. Map of Florida Bay and Whitewater Bay showing the sampling stations.

trees (up to 25 m); mainly red (*Rhizophora mangle*), black (*Avicennia germinans*), and white (*Laguncularia racemosa*) mangroves (Smith et al. 1994). The mangrove forest is a continuous band that stretches about 15 km inland from the coast. The bottom of the embayments in this region is largely calcareous mud, with occasional seagrass beds. Oyster bars are common within the area. It almost seems unreasonable to compare mangrove-lined Whitewater Bay area to Florida Bay's lagoonal structure, however, they are alike in that they exist in near identical climatic conditions, receive fresh water via a diffusive slough system arising from the Everglades, and have similar tidal exchange with the Shelf waters.

A total of 28 sample stations were located across Florida Bay (Fig. 1). Another 22 stations in the Whitewater Bay area were assigned so as to provide a gradient from fresh water to estuary throughout the many rivers in the region. Stations in Florida Bay were sampled semi-monthly from July 1989 to December 1990 and then monthly from March 1991 to July 1995; Whitewater Bay was sampled monthly from October 1992 to July 1995. Four days were required for each full sampling event.

ANALYTICAL METHODS

Surface salinity and temperature were measured using a combination salinity-conductivity-temperature probe (Orion model 140). Dissolved oxygen (DO, mg l^{-1}) was measured 10 cm below the surface using an oxygen electrode (Orion model 840) corrected for salinity and temperature.

Duplicate, unfiltered water samples were collected from 10 cm below the surface in acid-washed and sample-rinsed 150-ml HDPE bottles and kept at ambient temperature in the dark during transport. Duplicate water samples for dissolved nutrient analysis were collected using acid-washed and sample-rinsed 150-ml syringes. Samples were filtered (25-mm glass-fiber GF/F) by hand into acid-washed and sample-rinsed 60-ml HDPE bottles, which were capped and immediately placed on ice in the dark for transport. The wet filters, used for chlorophyll *a* (Chl *a*) analysis, were placed in 1.8-ml plastic centrifuge tubes to which 1.5 ml of 90% acetone was added (Strickland and Parsons 1972); they were then capped and put into a dark bottle placed on ice for transport.

Unfiltered water samples were analyzed for total

organic carbon (TOC), total nitrogen (TN), total phosphorus (TP), 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 $\text{pH} < 2$ and purging with CO_2 -free air. TN was measured using an ANTEK 7000N Nitrogen Analyzer using O_2 as the carrier gas instead of argon to promote complete recovery of the nitrogen in the water samples (Jones and Frankovich in press). TP was determined using a dry ashing, acid hydrolysis technique (Solórzano and Sharp 1980). The APA assay measures the activity of alkaline phosphatase, an enzyme used by bacteria to mineralize phosphate from organic compounds. The assay is performed by adding a known concentration of an organic phosphate compound (methylfluorescein phosphate) to an unfiltered water sample. Alkaline phosphatase in the water sample cleaves the phosphate, leaving methylfluorescein, a highly fluorescent compound. The fluorescence of initial and 2-h incubations were measured using a Gilford Fluoro IV Spectrofluorometer (excitation = 430 nm, emission = 507 nm) and subtracted to give APA ($\mu\text{M h}^{-1}$). 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 ammonium (NH_4^+) on a four-channel autoanalyzer (Alpkem model RFA 300). Filters for Chl *a* content ($\mu\text{g l}^{-1}$) were allowed to extract for a minimum of 2 d 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 wk after collection.

Some parameters were not measured directly but were calculated by difference. Nitrate (NO_3^-) was calculated as $\text{NO}_x^- - \text{NO}_2^-$. Total inorganic nitrogen (TIN) was calculated as $\text{NO}_x^- + \text{NH}_4^+$. Total organic nitrogen (TON) was defined as $\text{TN} - \text{TIN}$. All concentrations are reported as μM unless noted. All N:P ratios calculated and discussed in this paper are on a mole:mole basis.

STATISTICAL ANALYSES

To assess the underlying patterns in the distribution of the measured parameters, principal component analysis (PCA) was used to extract composite variables (principal components) from the original data (Overland and Preisendorfer 1982). The PCA solution was rotated (using VARIMAX) to facilitate the interpretation of the principal components, and the factor scores were saved for each data record. Spatial distribution of the mean and SD of the factor scores for each principal compo-

nent for each sampling station over the period of record were mapped using the kriging algorithm in Surfer (Golden Software). Both the mean and SD of the factor scores over the period of record for each station were then used as independent variables in a cluster analysis in order to aggregate stations into zones of similar influence (ZSI). The purpose of this analysis was to collapse the number of stations into a few groups which could then be analyzed in more detail.

Once stations were grouped by cluster analysis, statistical analysis of the water chemistry among ZSI was possible (see box-and-whiskers plots). 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. The box-and-whisker plot is a powerful statistic as it shows the median, range, distribution of the data as well as serving as a graphical, non-parametric ANOVA. In addition, differences in parameters among ZSI were quantified using Kruskal-Wallis test with significance set at $p < 0.05$.

Results

RANGES AND MEDIANS OF DATA

Large ranges in most measured parameters were the norm owing to the wide spatial and temporal sampling plan (Table 1). Medians are reported as the nonparametric statistic of comparison due to the skewed nature of most water chemistry data (see Christian et al. 1991). On average, the region was warm and hyposaline, with a median temperature of 26.6°C and a median salinity of 26.8‰. The median DO was 6.3 mg l^{-1} , or ~88% saturation. Inorganic N concentrations were a small fraction (6%) of the TN pool, with TON making up the bulk. NH_4^+ was the dominant inorganic N species in almost all of the samples (63% of TIN). SRP concentrations were very low (median $0.04 \mu\text{M}$) and composed only 8% of the TP pool. Chl *a* concentrations were low overall, $1.3 \mu\text{g l}^{-1}$, and ranged from 0.02 to $17.8 \mu\text{g l}^{-1}$. Ratios of N to P suggested a general P limitation of the water column; the median TN:TP was 120, and the median TIN:SRP was 70.

PRINCIPAL COMPONENT ANALYSIS

Principal component analysis (PCA) identified five composite variables (hereafter called PC_1 , PC_2 , 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),

TABLE 1. Summary statistics for all observations, 1989–1995. MAD = median absolute deviation; BD = below detection.

Parameter	Median	MAD	Minimum	Maximum	n
Temperature (°C)	26.6	3.0	9.3	35.3	2,588
Salinity (‰)	26.8	9.9	0.0	63.0	2,595
Dissolved oxygen (mg l ⁻¹)	6.3	0.9	1.3	15.2	2,552
NO ₃ ⁻ (μM)	0.46	0.40	BD	19.17	2,575
NO ₂ ⁻ (μM)	0.19	0.10	BD	7.60	2,592
NH ₄ ⁺ (μM)	2.09	1.32	BD	120.0	2,587
Total inorganic nitrogen (μM)	3.32	2.11	0.06	120.5	2,569
Total organic nitrogen (μM)	50.27	13.33	2.57	311.0	2,566
Total nitrogen (μM)	56.72	14.48	7.00	314.9	2,593
Soluble reactive phosphorus (μM)	0.04	0.02	BD	1.10	2,575
Total phosphorus (μM)	0.49	0.22	0.02	4.21	2,589
Total organic carbon (μM)	872.3	322.8	99.9	5,334	2,578
Alkaline phosphatase (μM h ⁻¹)	0.44	0.29	0.01	6.44	2,461
Chlorophyll <i>a</i> (μg l ⁻¹)	1.31	0.71	0.02	17.78	2,518
Turbidity (NTU)	3.70	2.46	0.01	178.6	2,462
TN:TP	116.9	53.0	6.5	2,197	2,566
TIN:SRP	70.6	53.5	-0.8	9,436	2,575

indicate five separate modes of variation in the data. PC_I had high factor loadings for TN, TON, APA, and TOC and was therefore designated as the "organic" component. PC_{II} was composed of NO₂⁻, NO₃⁻, and NH₄⁺ and was called the "inorganic nitrogen" component. Turbidity, TP, and Chl *a* were highly correlated with the "phytoplankton" PC_{III} component. PC_{IV} was positively correlated with temperature and negatively correlated with dissolved oxygen concentration. Salinity was the only variable included in PC_V. Concentration of SRP was not included in any of the principle components. The five principal components accounted for 71.8% of the total variance of the original variables.

Spatial distributions of the mean factor score for each station indicate how the average water quality varies over the study area (Fig. 2). The organic component showed a peak in the center of Florida Bay, with decreasing magnitude to the east, south, and west. The inorganic nitrogen component had two peaks: one in northeast Florida Bay, and the other in Coot Bay. The phytoplankton component was highest along the western margin of the study area. High values of PC_{IV}, correlated with low DO and high temperature, were found in the mangrove-lined estuaries north of Whitewater Bay. The salinity component (PC_V) generally decreased from the north to south, with a maximum in central Florida Bay.

The SD of the factor scores at each station indicate the degree of variability of each factor score over the 6 yr of monitoring (Fig. 3). The organic component was quite constant across the study area, with the exception of very high variability at two sites in northeastern Florida Bay. The inorganic nitrogen component was much more variable in Whitewater Bay and the mangrove-lined estuaries

in the northwestern section of the study area than in Florida Bay. The center of Florida Bay and Whitewater Bay exhibited high variability in the phytoplankton component. Western and Core Florida Bay were the most variable areas for the DO-temperature component. Salinity was the most variable in northeastern Florida Bay.

CLUSTER ANALYSIS

A hierarchical clustering algorithm, using the mean and SD of the five factor scores from each site, objectively grouped the 50 sampling sites into six groups having similar water chemistry or zones of similar influence (ZSI; Fig. 4). The level at which branching of the dendrogram occurred indicates the relative similarities of the ZSI. Water quality characteristics at the Coot Bay site (station 50; Fig. 1) were sufficiently different so as to be distinct. The four stations in the north-central region of Florida Bay that grouped together were called Core Bay. The next cluster, containing 22 stations in Florida Bay, was further separated into two ZSI. The "Eastern Bay" ZSI comprised 16 stations distributed in northeast through south Florida Bay along the main line of the Florida Keys. The "Western Bay" ZSI was made up of six stations in the extreme western part of the bay that is open to the Gulf of Mexico. All of the stations along the southwest coast or Whitewater Bay area formed a cluster, which was further divided into two ZSI: an Inner Mangrove and an Outer Mangrove area (Fig. 4). Interestingly, the station at the mouth of the C-111 canal in northeast Florida Bay (station 7; Fig. 1) was included in the Inner Mangrove ZSI.

WATER QUALITY CHARACTERISTICS AMONG ZSI

The organic component (PC_I), composed of TN, TON, APA, and TOC, explained 27% of the

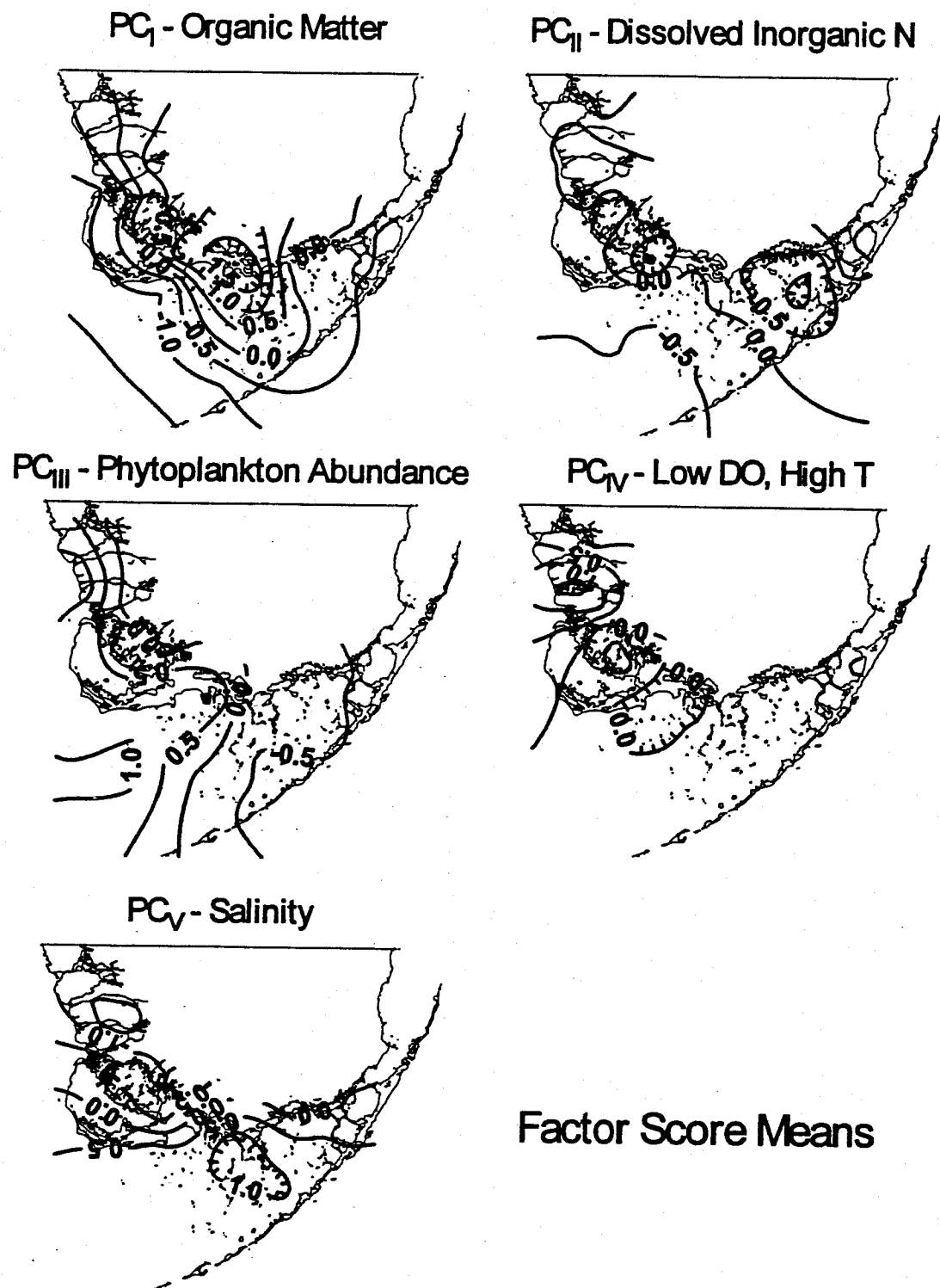


Fig 2. Set of maps, showing the spatial distributions of the mean factor scores for the five retained principal components. Hatchures point toward higher values.



Fig 3. Set of maps, showing the spatial distributions of the SD of the factor scores for the five retained principal components. Hatchures point toward higher values.

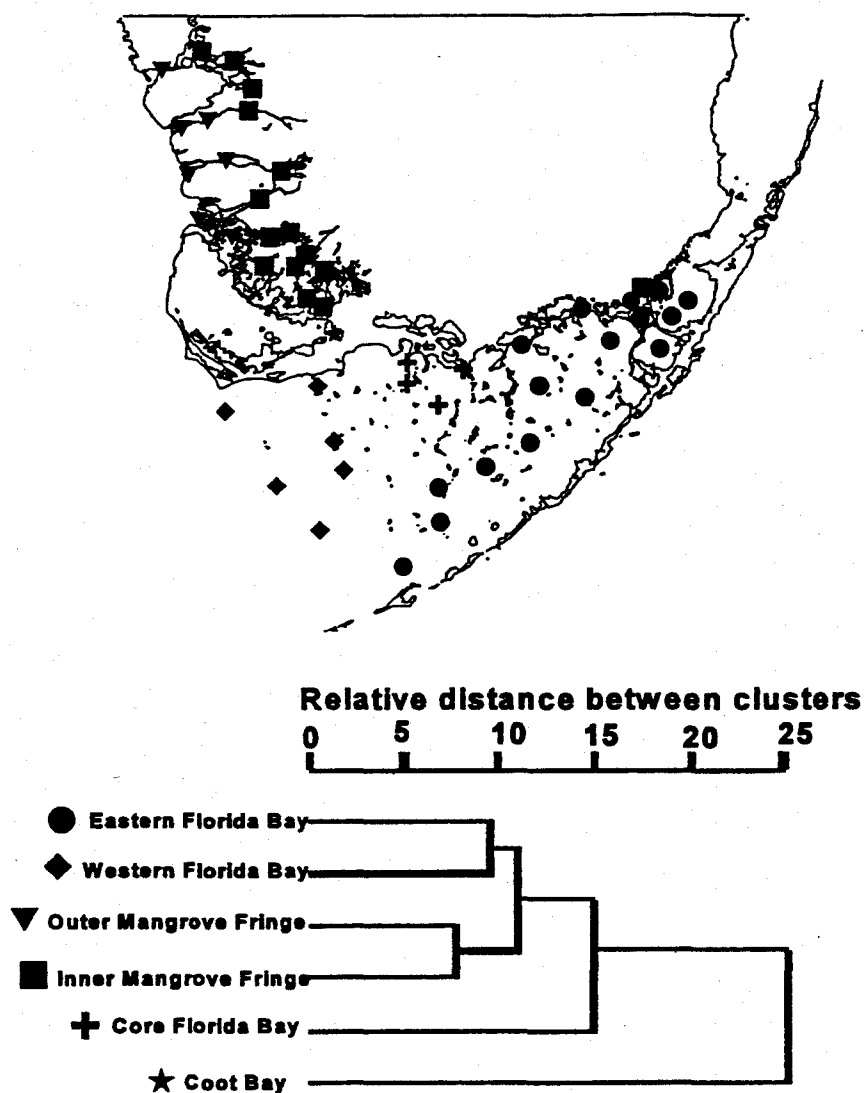


Fig. 4. Map and cladogram of zones of similar influence (ZSI) as a result of cluster analysis of mean and SD of five retained principal component scores.

variance in the original dataset (Table 2). The similarity in pattern among these four parameters across ZSI is striking (Fig. 5). TN and TON concentrations in the Core Bay were significantly higher than Eastern Bay ($p = 0.008$ and 0.01), which in turn were greater than Western Bay ($p = 0.001$ and 0.002). TN and TON levels in Coot Bay were greater than the Inner Mangrove ($p = 0.003$), which in turn were greater than the Outer Mangrove zone ($p = 0.009$). The strong correspondence between TN and TON was because almost all of the TN pool was present as TON (Table 1). Alkaline phosphatase activity in Florida Bay was highest in the Core Bay ($3.10 \mu\text{M h}^{-1}$, $p = 0.04$ and 0.02) with Eastern and Western bays not significantly different from each other (Fig. 5). While

in Whitewater Bay, the APA in Coot Bay was greater than Inner Mangrove ($p = 0.04$), which in turn were greater than the Outer Mangrove zones ($p = 0.01$). TOC concentrations followed a similar trend in concentration and statistical significance, with the Core Bay ($1355 \mu\text{M}$) greater than Eastern Bay ($713 \mu\text{M}$); these in turn, were greater than the Western Bay ($419 \mu\text{M}$). In the Whitewater Bay area, Coot Bay had the highest median TOC overall ($2013 \mu\text{M}$; $p = 0.01$ and 0.01), with lower concentrations in the Inner Mangrove and Outer Mangrove zones ($1355 \mu\text{M}$ and $1147 \mu\text{M}$; $p = 0.03$).

Water quality variables with high loadings on the "inorganic nitrogen" component (PC_{II}) were NO_2^- , NO_3^- , and NH_4^+ (Table 2). NO_2^- concentrations were highest in Eastern Bay ($0.24 \mu\text{M}$; p

TABLE 2. Results of principal component analysis shown as factor loadings for the first five principal components after VARIMAX rotation^a.

Parameter	Principal Component				
	PC _I	PC _{II}	PC _{III}	PC _{IV}	PC _V
Total nitrogen	0.93	0.17	0.07	0.12	0.00
Total organic nitrogen	0.92	-0.06	0.10	0.14	-0.08
Alkaline phosphatase	0.72	-0.08	0.22	-0.21	0.19
Total organic carbon	0.71	0.03	0.13	0.13	-0.47
NO ₂ ⁻	-0.03	0.84	0.03	-0.06	-0.11
NO ₃ ⁻	-0.10	0.75	0.07	0.04	-0.39
NH ₄ ⁺	0.12	0.67	-0.12	-0.04	0.38
Turbidity	-0.01	0.07	0.78	-0.19	0.25
Total phosphorus	0.33	-0.07	0.75	0.23	-0.27
Chlorophyll <i>a</i>	0.46	-0.13	0.65	-0.07	-0.15
Dissolved oxygen	0.01	0.00	-0.13	-0.87	0.10
Temperature	0.14	-0.17	-0.20	0.75	0.19
Salinity	-0.09	-0.10	-0.28	0.06	0.85
Soluble reactive phosphorus	0.04	0.11	0.37	0.31	-0.28
Percent Total Variance	27.0	14.7	11.5	10.5	8.1

^a Cumulative variance explained = 71.8%.

= 0.02) relative to Western and Core bays (0.12 μM and 0.12 μM ; $p = 0.35$; Fig. 6). NO₂⁻ in the Outer Mangrove zone (0.27 μM) was significantly higher than the Inner Mangrove (0.20 μM ; $p = 0.03$) while the Coot Bay station was highly variable with concentrations as high as 7.6 μM . Median NO₃⁻ concentrations in Eastern Bay (0.79 μM ; Fig. 6) were significantly greater ($p = 0.02$) than both Western and Core bays (0.24 μM and 0.28 μM ; p

= 0.43). NO₃⁻ concentrations increased from Inner Mangrove (0.84 μM) to the Outer Mangrove area (1.79 μM ; $p = 0.02$), with Coot Bay being lowest but highly variable (0.63 μM ; $p = 0.53$). NH₄⁺ concentrations in the Eastern Bay (3.49 μM , Fig. 6) were significantly greater than Western Bay (1.2 μM ; $p = 0.01$). The Core Bay was highly variable with concentrations as high as 120 μM . Both Inner Mangrove and Outer Mangrove zones had

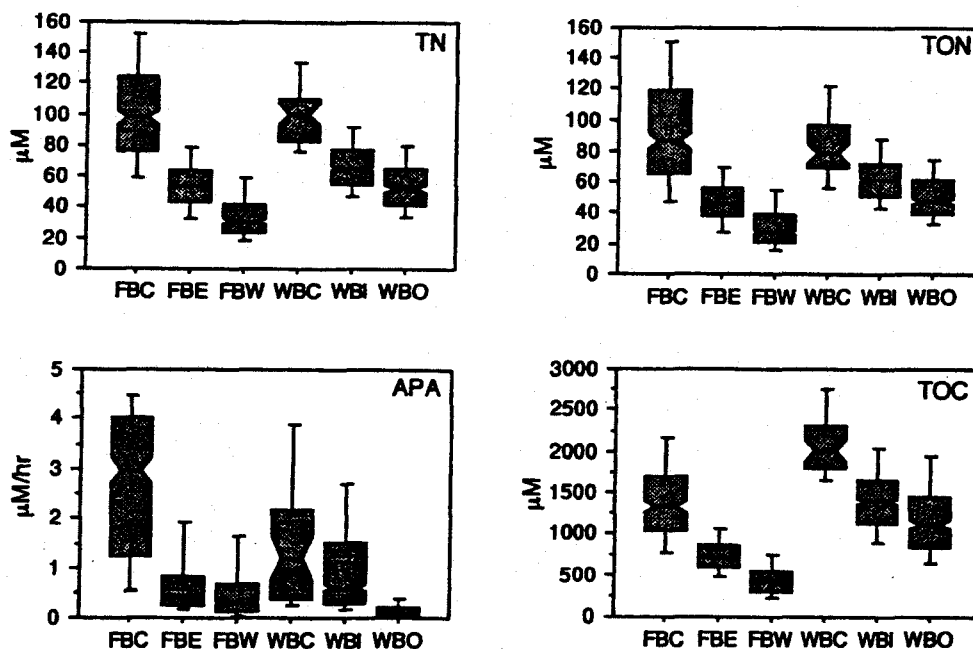


Fig. 5. Box-and-whisker plots of PC_I factors: TN (μM), TON (μM), APA ($\mu\text{M h}^{-1}$), and TOC (μM). The center horizontal line in the box is the median, the top and bottom of the box are the 25th and 75th percentiles (quartiles), and the ends of the whiskers are the 5th and 95th percentiles. The notch is the 95% confidence interval of the median. FBC = Core Florida Bay, FBE = Eastern Florida Bay, FBW = Western Florida Bay, WBC = Coot Bay, WBI = Inner Mangrove zone of Whitewater Bay, and WBO = Outer Mangrove zone.

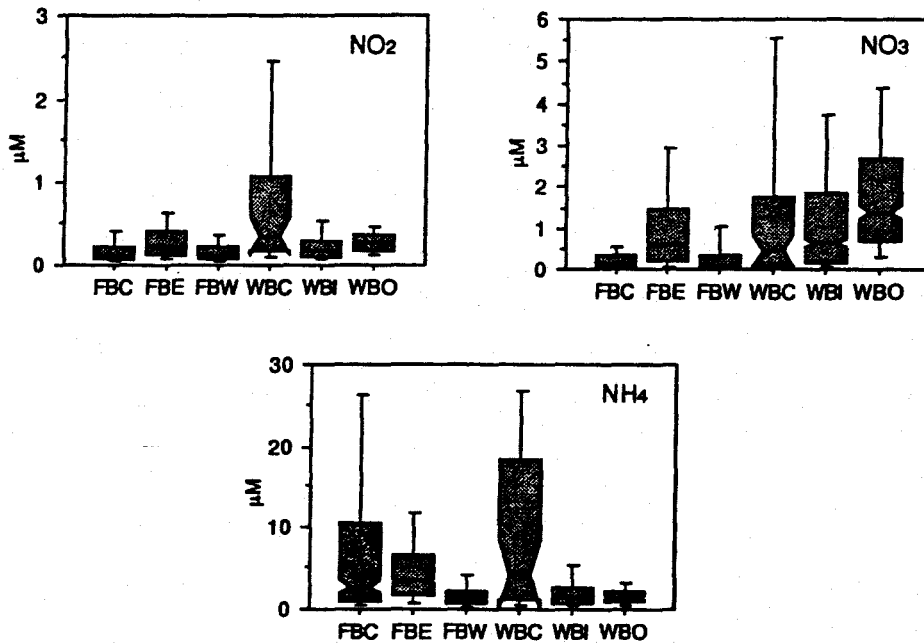


Fig. 6. Box-and-whisker plots of PC_{II} factors: NO₂⁻ (μM), NO₃⁻ (μM), and NH₄⁺ (μM).

comparable NH₄⁺ levels (1.64 μM and 1.62 μM ; $p = 0.68$), but the Coot Bay station was much more variable (range 0.24–75 μM).

Turbidity, TP, and Chl *a* were the three elements which made up the phytoplankton component (PC_{III}). Turbidities in both Western Bay (7.33 NTU) and Core Bay (5.76 NTU) were significantly higher than Eastern Bay (2.33 NTU; Fig. 7). In Whitewater Bay, the Coot Bay station had highest

overall turbidity (6.50 NTU), with lower concentrations in the Inner Mangrove and Outer Mangrove zones (3.10 and 4.90 NTU); however, these differences were not significant. TP in the Core Bay was significantly greater than Western Bay ($p = 0.02$), which in turn was significantly higher than the Eastern Bay ($p = 0.05$; Fig. 7). Both Coot Bay (1.04 μM) and the Outer Mangrove zone (0.97 μM) had significantly higher TP concentrations

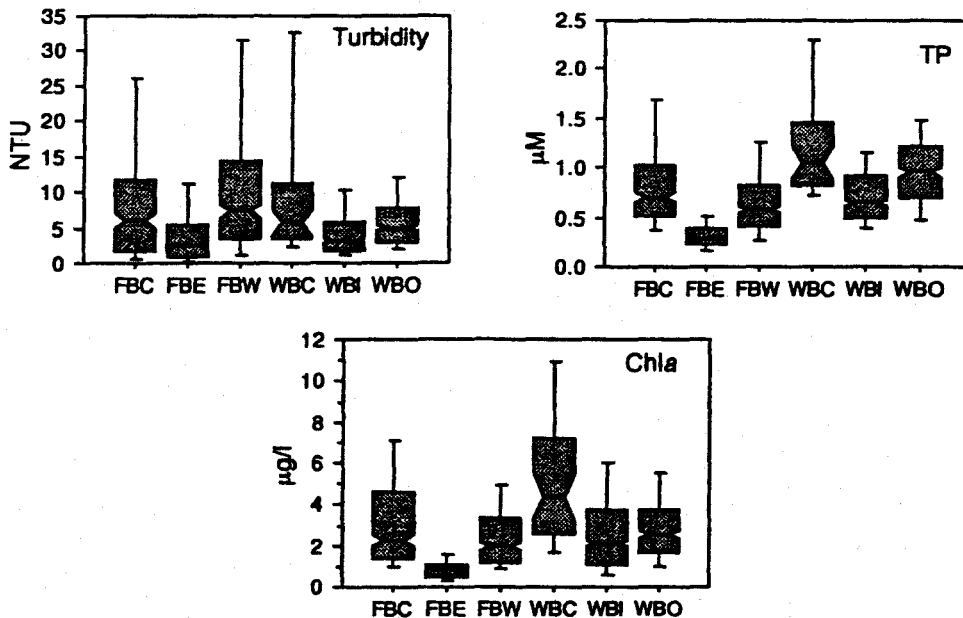


Fig. 7. Box-and-whisker plots of PC_{III} factors: turbidity (NTU), TP (μM), and Chl *a* ($\mu\text{g l}^{-1}$).

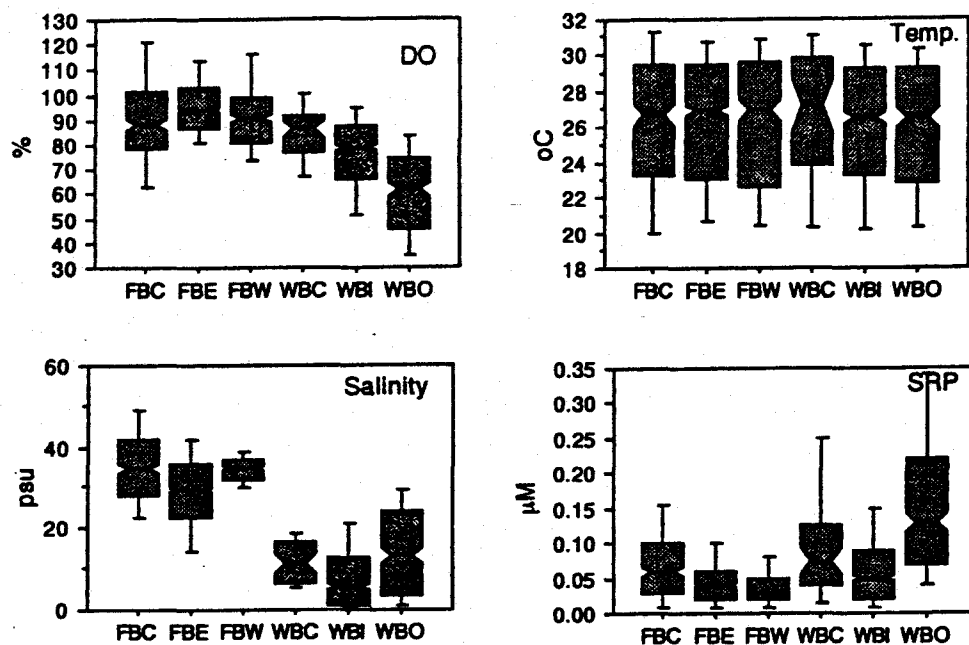


Fig. 8. Box-and-whisker plots of PC_{IV} and PC_V factors: DO saturation (%), temperature ($^{\circ}C$), and salinity (‰). SRP (μM) was not a factor in the PCA results.

than the Inner Mangrove ($0.63 \mu M$). Chl *a* concentrations in the Eastern Bay ($0.90 \mu g l^{-1}$) were significantly lower than both Western and Core bays ($1.98 \mu g l^{-1}$ and $2.28 \mu g l^{-1}$; Fig. 7). Median Chl *a* at the Coot Bay station ($4.34 \mu g l^{-1}$) was significantly greater than both Inner Mangrove and Outer Mangrove zones ($2.00 \mu g l^{-1}$ and $2.31 \mu g l^{-1}$), and had a maximum concentration of $17.78 \mu g l^{-1}$.

DO concentrations in Eastern Bay ($6.7 mg l^{-1}$) were significantly higher than those in Western Bay ($6.2 mg l^{-1}$; $p = 0.04$) and Core zones ($6.1 mg l^{-1}$; $p = 0.02$). The Core Bay had both lowest and highest measured DO for Florida Bay during the period of record ($1.3 mg l^{-1}$ and $15.2 mg l^{-1}$). The Outer Mangrove zone ($4.8 mg l^{-1}$) had significantly lower DO than the Inner Mangrove ($6.2 mg l^{-1}$; $p = 0.02$) which was < Coot Bay ($6.6 mg l^{-1}$). DO saturation (Fig. 8) followed a slightly different trend than DO, mostly as a function of salinity. DO saturation in Eastern Bay (93.9%) was significantly higher than that of Western and Core zones (90.8% and 87.9%). The Core Bay had the lowest and highest measured DO saturation in Florida Bay for the period of record (38.8% and 170.7%). The Outer Mangrove zone had significantly lower DO saturation (61.8%) than both Inner Mangrove and Coot Bay (78.7 and 86.2%). Median water temperature was not significantly different among zones (Fig. 8) but was most variable in Coot Bay.

Salinity was generally higher in Florida Bay than in the Mangrove zones, reflecting the difference

between the lagoonal Florida Bay ecosystem and the estuaries of the southwest Florida coast (Fig. 8). Median salinity was highest and most variable in the Core Bay (35.8‰, range 9–63‰), being hypersaline ~50% of the time. Salinity was lowest in the Eastern Bay (30.2‰) while Western Bay (35.3‰) was similar to the Gulf of Mexico and had a more narrow range (25–51‰). Salinity in the estuarine mangrove zones of the Whitewater Bay area were more influenced by freshwater run-off from the mainland and were generally less than 25‰. The Inner Mangrove zone (7.1‰) had significantly lower salinities than the Outer Mangrove (14.6‰; $p = 0.03$). Coot Bay displayed a narrow range of salinity and was intermediate to both Inner Mangrove and Outer Mangrove zones. SRP concentrations were very low in all of the zones (Fig. 8), with most of Florida Bay generally being < $0.1 \mu M$. SRP was much higher in the Outer Mangrove ($0.14 \mu M$) than the Inner Mangrove zone ($0.05 \mu M$; $p = 0.01$).

The median TIN:SRP and TN:TP ratios (Fig. 9) of Eastern Bay (123 and 180, respectively) were significantly higher than both Western Bay (52 and 53) and Core Bay (48 and 128). In Whitewater Bay, N:P ratios indicated that the Inner Mangrove zone was potentially more P-limited than the Outer Mangrove zone ($p = 0.02$ and 0.01), with Coot Bay being highly variable.

Discussion

The process of using principal component analysis in combination with multivariate cluster anal-

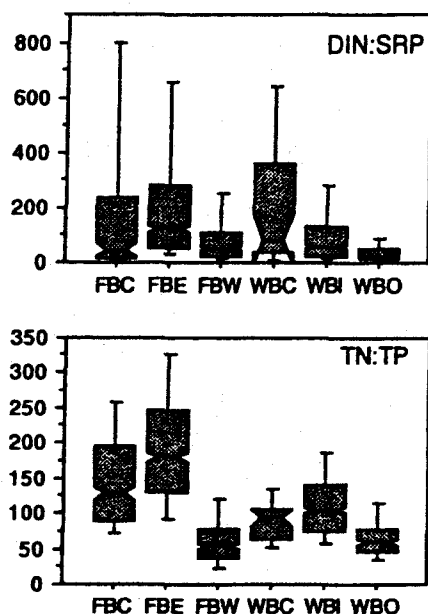


Fig. 9. Box-and whisker plots of molar ratios of TIN:SRP and TN:TP.

ysis has been shown to be a useful method of aggregating spatially distributed sampling stations into zones possessing similar water-quality characteristics. Previously, investigators have relied on their own familiarity with an ecosystem or on anecdotal evidence in order to group spatially explicit stations for comparative purposes. The most common method used in estuaries has been that of grouping by salinity zones (e.g., polyhaline, mesohaline, etc.). This is useful only when there is an a priori reason to do so, as with species tolerance limits (Bulger et al. 1993) or because of the existence of linear and/or longitudinal salinity gradients in river-dominated estuaries. In lagoonal estuaries, however, freshwater inputs are usually smaller and more diffuse, making tidal and wind mixing more important to water circulation and residence time. By objectively defining a ZSI, it is possible to class different areas of such a water body into functionally distinct zones. Such a classification is often necessary for statistically interpreting large datasets or for designing replicated experiments. The fact that the ZSI defined for Florida Bay are similar to sub-environments based on mollusc distributions (Turney and Perkins 1972), seagrass communities (Zieman et al. 1989), and fish communities (Thayer and Chester 1989), and are complementary to what we know of the hydrology of the system, lends credence to this classification process. That these station groupings were spatially contiguous supports our observations of comparable influence from allochthonous and autochthonous sources. This is no substitute

for actual measurement of nutrient cycling rates and fluxes but it does allow us to generate new hypotheses as to their contribution to water quality.

Using this approach, Florida Bay was divided into three distinct ZSI: Eastern Florida Bay, Core Florida Bay, and Western Florida Bay. The estuarine waters of the mangrove-dominated coast of extreme southwestern Florida were divided into two distinct zones: Inner Mangrove (landward) and Outer Mangrove (seaward). While standard estuarine grouping using salinity range may have resulted in a similar definition of zones in the mangrove fringe, the grouping of stations in Florida Bay would have remained unresolved. The magnitude and variability of the principal components, in conjunction with knowledge of hydrographic inputs, allows for interpretation of the most important processes influencing water quality in the distinct zones.

One of the purposes of any monitoring program should be to use the data gained by routine sampling to extend our understanding of the system by developing new hypotheses as to the underlying processes which drive it. Much inference into the behavior of Florida Bay-Whitewater Bay can be made from the observed magnitude and distribution of water quality parameters.

EASTERN BAY

The Eastern Bay ZSI was characterized by a wide salinity range (0.2–53.0‰) indicative of a freshwater-seawater mixing zone. Depending on the season and year, portions of Eastern Bay were almost entirely fresh water or hypersaline. Spatial analyses of individual sampling dates show a gradient of increasing salinity in a northeast to southwest direction, in response to freshwater runoff from the Taylor Slough and C-111 canals. Robblee et al. (1989) also came to this conclusion in their analysis of salinity records from 1957–1988. The freshwater input to Eastern Bay was also reflected in its having generally higher concentrations of NO_3^- , NO_2^- , NH_4^+ , TON, and TOC than Western Bay (Figs. 5 and 6). We can infer from the data that Eastern Bay receives N from terrestrial sources in runoff and is an area with an active N cycle where ammonification, nitrification, and denitrification are evident; however, it is possible that P availability may cause some rate limitation.

TP was lower in Eastern Bay than in the other zones mostly as a result of the low P loading from Taylor Slough and the C-111 canal (D. Rudnick personal communication). SRP concentrations were very low, often near or below the detection limit ($0.01 \mu\text{M}$), but were comparable to other zones of Florida Bay. Both TP and Chl *a* covaried as determined by PCA. Low levels of TP did not

correlate well with high APA, nor was there a significant negative relationship between SRP and APA in Eastern Bay. However, since we did not count bacteria, we do not know if the low APA was due to smaller bacterial numbers. It is possible that other factors in addition to low P concentration may be important in determining both bacterial abundance and exoenzyme production in this region (see below).

Eastern Bay had highest TIN:SRP and TN:TP ratios, indicating the severity of P limitation in this area of Florida Bay. This was also reflected in its having the lowest standing stock of phytoplankton (as measured by Chl *a*) of the three ZSI. Eastern Bay also had the lowest overall turbidity than the other Florida Bay ZSI.

CORE BAY

The Core Florida Bay ZSI is an area of low freshwater runoff and restricted water circulation due to the surrounding mud banks. The long water residence time in this area, especially in summer when winds are light, allows for high evaporation rates and results in persistent hypersaline events (up to 63‰ for this period of record). The Core Bay is the portion of Florida Bay that has experienced widespread cyanobacterial blooms in recent years (Philips and Badylak 1996). This ZSI is characterized by very high concentrations of TON, TOC, and NH_4^+ , elevated TP, Chl *a*, and APA; and very low levels of NO_3^- and NO_2^- . Analysis of our 7-yr, monthly database has shown no significant temporal trend in TON or TOC in this ZSI (unpublished data), therefore, the high concentrations of TOC and TON are a persistent feature of this area. This is most probably due to the extended water residence time and evaporative nature of this area which acts to concentrate solutes.

High NH_4^+ levels in this shallow area (up to 120 μM) may be due to long water residence time, rapid benthic remineralization of NH_4^+ , and possibly inhibition of nitrification by photoproduction of carbon monoxide (Vanzella et al. 1989). Highest NH_4^+ concentrations occur during November to April and highest salinities occur during May to October, ruling out extended water residence time and salinity-inhibited nitrification as important determinants. High rates of benthic NH_4^+ flux have been measured in the northern mangrove boundary of Florida Bay (D. Rudnick personal communication). No measurements have been made in the Core Bay but there is much potential for the high phytoplankton biomass to fuel a large amount of NH_4^+ remineralization. In addition, the very low concentrations of NO_3^- and NO_2^- implies incomplete N cycling rather than simply a large amount of benthic NH_4^+ remineralization. It is possible

that denitrification is limited by the rates of nitrification. We plan to follow up on the hypothesis that strong sunlight on a shallow water column containing high DOC concentrations promotes high levels of CO, and that this CO by diffusive flux into the sediments will result in a repressed rate of nitrification, a greatly diminished amount of coupled denitrification (due to low NO_3^-), and the accumulation of NH_4^+ in the system.

Highest AP activities measured in Florida Bay occurred in the Core Bay and were related more to TOC and TON than to TP (Fig. 5). No significant relationship was observed between APA and SRP, most probably because SRP concentrations are always so low as to be almost undetectable. APA was an order of magnitude greater in Core than Western Bay but concentrations of TP were comparable (median 0.7 μM and 0.6 μM , respectively). It may be that the TP pool is not a good estimate of organic P in this system. A significant fraction of sediment-bound P measured by the TP analysis is probably not accessible by bacterial enzymes, therefore, the total contribution and quality of organic P in the TP pool may be very different among the three zones of Florida Bay. As a possible consequence of high APA, Core Bay had higher SRP concentrations than other areas of Florida Bay. Even with the existence of high N concentrations, Core Bay remains the least potentially P-limited area of Florida Bay (median TIN:SRP = 48).

As mentioned previously, Chl *a* values are relatively high in this region, with spikes up to 18 $\mu\text{g l}^{-1}$. There has been much concern by local management agencies as to the cause of this persistent phytoplankton bloom. Interestingly, the median Chl *a* concentration in the Core Bay is not significantly different than the Western Bay; however, the phytoplankton communities are markedly distinct. Phytoplankton in the Core Bay are mostly composed of the cyanobacteria *Synechococcus*, while a mixed community of diatoms and dinoflagellates dominate the Western Bay (Philips and Badylak 1996; C. Tomas personal communication). The difference between phytoplankton communities may have profound effects on the trophic transfer and secondary production in these regions.

WESTERN BAY

Median salinity in Western Bay was comparable to Core Bay but was much less variable. In addition, the low concentrations of TN, TON, APA, TOC, NO_3^- , NO_2^- , and NH_4^+ characterize this region as being influenced primarily by the Shelf waters (unpublished data). Western Bay had higher TP concentrations than Eastern Bay as a result of more marine influence but was lower than the Core Bay. SRP concentrations were lower than

Core Bay but, because of low N concentrations, exhibited comparable N:P ratios. As a consequence of relatively high TP, concentrations of Chl *a* in Western Bay were relatively high, being similar to Core Bay but much higher than in the Eastern Bay. Turbidity in Western Bay was higher than Eastern Bay which may have been due to increased wind exposure and tidal amplitude in this zone. There is also some evidence that the recent seagrass die-off in this region has destabilized the sediment, allowing for more tidal and wind-driven resuspension.

COOT BAY

The Coot Bay ZSI does not merit much discussion as it is a single station located in a small, almost completely enclosed bay. In 1957, Coot Bay was connected to Florida Bay by the Buttonwood canal dug through the mangroves. In 1982 the canal was plugged at the Florida Bay end making it hydraulically isolated from both Whitewater and Florida Bays. Like Core Florida Bay, Coot Bay has a long water residence time, which may account for the high concentrations of TN, TON, TOC, NH_4^+ , TP, and Chl *a* measured there. It is not unreasonable to attribute these water quality characteristics to the physical and historical nature of the site (Tabb et al. 1962).

INNER MANGROVE FRINGE

Freshwater runoff from Shark River Slough in the Everglades coalesces into stream channels of the Inner Mangrove ZSI. Median salinity was 7‰, which characterizes it as the oligohaline zone of the southwest Florida coast (Bulger et al. 1993). Relatively high levels of TON and TOC existed in this region as a result of leaching from the surrounding mangrove forest (Fig. 5). Inorganic N was also low but contrary to Florida Bay, NO_3^- was the dominant species (Fig. 6). One possible explanation is that, being a blackwater area, nitrification is more pronounced due to reduced photoinhibition. TP and SRP were low in this area, but APA was high relative to the Outer Mangrove zone. This association of high APA with low TP is contrary to observations in Florida Bay.

OUTER MANGROVE FRINGE

The Outer Mangrove ZSI was composed of stations located primarily in the lower estuarine ends of the Shark, Broad, Harney, and Lostmans Rivers (Fig. 4). With a median salinity of 15‰, this ZSI can be considered the mesohaline-polyhaline zone. Salinity increased from Inner Mangrove to Outer Mangrove zone as was expected, but more importantly, NH_4^+ , NO_3^- , and NO_2^- show nonconservative distributions (relative to salinity), with

highest concentrations occurring in the Outer Mangrove zone (data not shown). This high standing stock of TIN may be the result of the mineralization of TON from autochthonous production within the mangrove zone, offshore advection of sediment N, or from upstream loading. Autochthonous TON production as the result of bacterial N-fixation in association with mangrove root systems or from cyanobacterial primary production in the water column has been shown to be low (Boto and Robertson 1990). Mangrove sediment data from the Shark River (Chen and Twilley in review) showed a decrease in TON and TOC from the Inner Mangrove to Outer Mangrove zone. Interestingly, as sediment TON declined, NH_4^+ in the sediment increased. This is consistent with our water column data and suggests that mineralization of sediment TON is the source of water column TIN. What remains unclear is the relative contribution of sediment N from upstream and offshore sources.

Concentrations of TP and SRP were also higher in the Outer Mangrove than Inner Mangrove zone. This down-estuary increase in P is also seen in the sediments (R. Twilley personal communication). TP and SRP from stations 2 km offshore on the Shelf (unpublished data) are low (0.41 μM and 0.04 μM , respectively), indicating that Shelf waters do not account for this increase. However, there may be significant, wind- and tide-driven sediment transport into this area which may act as a source of P to this region.

APA in the Outer Mangrove zone was lower than in any other ZSI (0.09 $\mu\text{M h}^{-1}$), as a direct result of high SRP and TP. Only in the Outer Mangrove zone was there a significant inverse relationship between SRP and APA ($p = 0.03$). Chl *a* concentrations were not significantly different between the Inner Mangrove and Outer Mangrove zone. This was interesting as concentrations of both TIN and SRP increased downstream and the median TIN:SRP ratio declined from 59 to 24. It is possible that high concentrations of mangrove-derived TOC in the Outer Mangrove zone, resulting in blackwater conditions, cause the phytoplankton in this region to be limited by light rather than nutrients.

Conclusions

The aggregation of 50 fixed monitoring stations into six ZSI according to physical, chemical, and biological similarity has provided us with a much clearer picture of the Florida Bay and Whitewater Bay ecosystems. Both systems are similar in that N and P are supplied via tidal mixing with Shelf waters and that P availability decreases with distance from the Shelf (Fourqurean et al. 1993). Differences between ecosystems are due mostly to mor-

phology and hydrology. The general view of Florida Bay emerging from this analysis is that of an ecosystem dominated by its restricted hydrology. The shallow banks inhibit water movement within the estuary, resulting in spatial heterogeneity in water quality. Mixing of fresh water occurs from a northeast-southwest direction. Input of Shelf water occurs via the Western Bay and is slowly transported to the northeast into the Core Bay where, depending upon rainfall, it is either entrained by the flow of water out of Florida Bay or evaporated, resulting in hypersaline conditions. In contrast, the mangrove forests of Whitewater Bay possess a well-developed channel system which culminates in a series of river-dominated estuaries. Tidal range and exchange is much greater in this area and results in obvious differences in salinity and nutrient distributions.

The above analysis documents the similarities and differences in water quality characteristics of Florida Bay and Whitewater Bay. This type of multivariate approach should prove useful to scientists and managers faced with the task of interpreting large water quality datasets. In addition, there are now statistical grounds to distinguish regions of Florida Bay and Whitewater Bay according to water quality; we suggest that future management practices take this into account.

ACKNOWLEDGMENTS

We thank Pete Lorenzo, Tom Frankovich, Jeff Absten, and all the other field and laboratory technicians involved with this project over the years. This study was supported by grants from the South Florida Water Management District and Everglades National Park. This is contribution #51 of the Southeast Environmental Research Program at Florida International University.

LITERATURE CITED

- BODLE, M. J., A. P. FERRITER, AND D. D. THAYER. 1994. The biology, distribution, and ecological consequences of *Melaleuca quinquenaria* in the Everglades, p. 341-356. In S. M. Davis and J. C. Ogden (eds.), *Everglades, The Ecosystem and Its Restoration*. St. Lucie Press, Delray Beach, Florida.
- BOSENCE, D. 1989. Surface sublittoral sediments of Florida Bay. *Bulletin of Marine Science* 44:434-453.
- BOTO, K. G. AND A. I. ROBERTSON. 1990. The relationship between nitrogen fixation and tidal exports of nitrogen in a tropical mangrove system. *Estuarine, Coastal and Shelf Science* 31:531-540.
- BULGER, A. J., B. P. HAYDEN, M. E. MONACO, D. M. NELSON, AND M. G. MCCORMICK-RAY. 1993. Biologically-based estuarine salinity zones derived from multivariate analysis. *Estuaries* 16:311-322.
- BUTLER, M. J. IV, J. V. HUNT, W. F. HERRNKIND, M. J. CHILDRESS, R. BERTELSON, W. SHARP, T. MATTHEWS, J. M. FIELD, AND H. G. MARSHALL. 1995. Cascading disturbances in Florida Bay, USA: Cyanobacteria blooms, sponge mortality, and implications for juvenile spiny lobsters, *Panulirus argus*. *Marine Ecology Progress Series* 129:119-125.
- CHRISTIAN, R. R., J. N. BOYER, D. W. STANLEY, AND W. M. RIZZO. 1991. Multi-year distribution patterns of nutrients in the Neuse River Estuary, North Carolina. *Marine Ecology Progress Series* 71:259-274.
- FOURQUREAN, J. W., G. V. N. POWELL, AND J. C. ZIEMAN. 1992a. Phosphorus limitation of primary production in Florida Bay: Evidence from the C:N:P ratios of the dominant seagrass, *Thalassia testudinum*. *Limnology and Oceanography* 37:162-171.
- FOURQUREAN, J. W., G. V. N. POWELL, AND J. C. ZIEMAN. 1992b. Relationships between porewater nutrients and seagrasses in a subtropical carbonate environment. *Marine Biology* 114:57-65.
- FOURQUREAN, J. W., R. D. JONES, AND J. C. ZIEMAN. 1993. Processes influencing water column nutrient characteristics and phosphorus limitation of phytoplankton biomass in Florida Bay, FL, USA: Inferences from spatial distributions. *Estuarine, Coastal and Shelf Science* 36:295-314.
- HARDIN, M. M., H. A. RINES, C. E. ROSE, AND M. B. ABEL. 1996. Spatial heterogeneity of macrophytes and selected invertebrates in Narragansett Bay (RI, USA) as revealed by principal component and cluster analyses. *Estuarine, Coastal and Shelf Science* 42:123-134.
- JACKILEE, J. B. AND D. R. HAMILTON. 1977. Objective analysis and classification of oceanographic data. *Tellus* 29:545-560.
- JONES, R. D., AND T. A. FRANKOVICH. In press. A rapid, precise, and sensitive method for the determination of total nitrogen in natural waters. *Marine Chemistry*.
- LAPOINTE, B. E. AND M. W. CLARK. 1992. Nutrient inputs from the watershed and coastal eutrophication in the Florida Keys. *Estuaries* 15:465-476.
- OVERLAND, J. E. AND R. W. PREISENDORFER. 1982. A significance test for principal components applied to cyclone climatology. *Monthly Weather Review* 110:1-4.
- PHILIPS, E. J. AND S. BADYLAK. 1996. Spatial variability in phytoplankton standing stock and composition in a shallow inner-shelf lagoon, Florida Bay, Florida. *Bulletin of Marine Science* 58:203-216.
- POWELL, G. V. N., W. J. KENWORTHY, AND J. W. FOURQUREAN. 1989. Experimental evidence for nutrient limitation of seagrass growth in a tropical estuary with restricted circulation. *Bulletin of Marine Science* 44:324-340.
- ROBBLEE, M. B., J. T. TILMANT, AND J. EMERSON. 1989. Quantitative observations on salinity. *Bulletin of Marine Science* 44:523.
- ROBBLEE, M. B., T. B. BARBER, P. R. CARLSON JR., M. J. DURAKO, J. W. FOURQUREAN, L. M. MUEHLSTEIN, D. PORTER, L. A. YABRO, R. T. ZIEMAN, AND J. C. ZIEMAN. 1991. Mass mortality of the tropical seagrass *Thalassia testudinum* in Florida Bay (USA). *Marine Ecology Progress Series* 71:297-299.
- SMITH, T. J. III, M. B. ROBBLEE, H. R. WANLESS, AND T. W. DOYLE. 1994. Mangroves, hurricanes, and lightning strikes. *BioScience* 44:256-262.
- SOLÓRZANO, L., AND J. H. SHARP. 1980. Determination of total dissolved phosphorus and particulate phosphorus in natural waters. *Limnology and Oceanography* 25:754-758.
- STRICKLAND, J. D. H., AND T. R. PARSONS. 1972. A practical handbook of seawater analysis. *Bulletin of the Fisheries Research Board of Canada* 167:107-112.
- TABB, D. C., D. L. DUBROW, AND R. B. MANNING. 1962. The ecology of northern Florida Bay and adjacent estuaries. Technical Series No. 39, Board of Conservation, State of Florida, Miami, Florida.
- THAYER, G. W., AND A. J. CHESTER. 1989. Distribution and abundance of fishes among basin and channel habitats in Florida Bay. *Bulletin of Marine Science* 44:200-219.
- TURNER, W. J., AND R. F. PERKINS. 1972. Molluscan distributions in Florida Bay. Sedimenta III, Comparative Sedimentology Laboratory, University of Miami, Florida.
- VANZELLA, A., M. A. GUERRERO, R. D. JONES. 1989. Effect of CO and light on ammonium and nitrite oxidation by chemolithotrophic bacteria. *Marine Ecology Progress Series* 57:69-76.

Core Bay but, because of low N concentrations, exhibited comparable N:P ratios. As a consequence of relatively high TP, concentrations of Chl *a* in Western Bay were relatively high, being similar to Core Bay but much higher than in the Eastern Bay. Turbidity in Western Bay was higher than Eastern Bay which may have been due to increased wind exposure and tidal amplitude in this zone. There is also some evidence that the recent seagrass die-off in this region has destabilized the sediment, allowing for more tidal and wind-driven resuspension.

COOT BAY

The Coot Bay ZSI does not merit much discussion as it is a single station located in a small, almost completely enclosed bay. In 1957, Coot Bay was connected to Florida Bay by the Buttonwood canal dug through the mangroves. In 1982 the canal was plugged at the Florida Bay end making it hydraulically isolated from both Whitewater and Florida Bays. Like Core Florida Bay, Coot Bay has a long water residence time, which may account for the high concentrations of TN, TON, TOC, NH_4^+ , TP, and Chl *a* measured there. It is not unreasonable to attribute these water quality characteristics to the physical and historical nature of the site (Tabb et al. 1962).

INNER MANGROVE FRINGE

Freshwater runoff from Shark River Slough in the Everglades coalesces into stream channels of the Inner Mangrove ZSI. Median salinity was 7‰, which characterizes it as the oligohaline zone of the southwest Florida coast (Bulger et al. 1993). Relatively high levels of TON and TOC existed in this region as a result of leaching from the surrounding mangrove forest (Fig. 5). Inorganic N was also low but contrary to Florida Bay, NO_3^- was the dominant species (Fig. 6). One possible explanation is that, being a blackwater area, nitrification is more pronounced due to reduced photoinhibition. TP and SRP were low in this area, but APA was high relative to the Outer Mangrove zone. This association of high APA with low TP is contrary to observations in Florida Bay.

OUTER MANGROVE FRINGE

The Outer Mangrove ZSI was composed of stations located primarily in the lower estuarine ends of the Shark, Broad, Harney, and Lostmans Rivers (Fig. 4). With a median salinity of 15‰, this ZSI can be considered the mesohaline-polyhaline zone. Salinity increased from Inner Mangrove to Outer Mangrove zone as was expected, but more importantly, NH_4^+ , NO_3^- , and NO_2^- show nonconservative distributions (relative to salinity), with

highest concentrations occurring in the Outer Mangrove zone (data not shown). This high standing stock of TIN may be the result of the mineralization of TON from autochthonous production within the mangrove zone, offshore advection of sediment N, or from upstream loading. Autochthonous TON production as the result of bacterial N-fixation in association with mangrove root systems or from cyanobacterial primary production in the water column has been shown to be low (Boto and Robertson 1990). Mangrove sediment data from the Shark River (Chen and Twilley in review) showed a decrease in TON and TOC from the Inner Mangrove to Outer Mangrove zone. Interestingly, as sediment TON declined, NH_4^+ in the sediment increased. This is consistent with our water column data and suggests that mineralization of sediment TON is the source of water column TIN. What remains unclear is the relative contribution of sediment N from upstream and offshore sources.

Concentrations of TP and SRP were also higher in the Outer Mangrove than Inner Mangrove zone. This down-estuary increase in P is also seen in the sediments (R. Twilley personal communication). TP and SRP from stations 2 km offshore on the Shelf (unpublished data) are low ($0.41 \mu\text{M}$ and $0.04 \mu\text{M}$, respectively), indicating that Shelf waters do not account for this increase. However, there may be significant, wind- and tide-driven sediment transport into this area which may act as a source of P to this region.

APA in the Outer Mangrove zone was lower than in any other ZSI ($0.09 \mu\text{M h}^{-1}$), as a direct result of high SRP and TP. Only in the Outer Mangrove zone was there a significant inverse relationship between SRP and APA ($p = 0.03$). Chl *a* concentrations were not significantly different between the Inner Mangrove and Outer Mangrove zone. This was interesting as concentrations of both TIN and SRP increased downstream and the median TIN:SRP ratio declined from 59 to 24. It is possible that high concentrations of mangrove-derived TOC in the Outer Mangrove zone, resulting in blackwater conditions, cause the phytoplankton in this region to be limited by light rather than nutrients.

Conclusions

The aggregation of 50 fixed monitoring stations into six ZSI according to physical, chemical, and biological similarity has provided us with a much clearer picture of the Florida Bay and Whitewater Bay ecosystems. Both systems are similar in that N and P are supplied via tidal mixing with Shelf waters and that P availability decreases with distance from the Shelf (Fourqurean et al. 1993). Differences between ecosystems are due mostly to mor-

phology and hydrology. The general view of Florida Bay emerging from this analysis is that of an ecosystem dominated by its restricted hydrology. The shallow banks inhibit water movement within the estuary, resulting in spatial heterogeneity in water quality. Mixing of fresh water occurs from a northeast-southwest direction. Input of Shelf water occurs via the Western Bay and is slowly transported to the northeast into the Core Bay where, depending upon rainfall, it is either entrained by the flow of water out of Florida Bay or evaporated, resulting in hypersaline conditions. In contrast, the mangrove forests of Whitewater Bay possess a well-developed channel system which culminates in a series of river-dominated estuaries. Tidal range and exchange is much greater in this area and results in obvious differences in salinity and nutrient distributions.

The above analysis documents the similarities and differences in water quality characteristics of Florida Bay and Whitewater Bay. This type of multivariate approach should prove useful to scientists and managers faced with the task of interpreting large water quality datasets. In addition, there are now statistical grounds to distinguish regions of Florida Bay and Whitewater Bay according to water quality; we suggest that future management practices take this into account.

ACKNOWLEDGMENTS

We thank Pete Lorenzo, Tom Frankovich, Jeff Absten, and all the other field and laboratory technicians involved with this project over the years. This study was supported by grants from the South Florida Water Management District and Everglades National Park. This is contribution #51 of the Southeast Environmental Research Program at Florida International University.

LITERATURE CITED

- BODLE, M. J., A. P. FERRITER, AND D. D. THAYER. 1994. The biology, distribution, and ecological consequences of *Melaleuca quinquenaria* in the Everglades, p. 341-356. In S. M. Davis and J. C. Ogden (eds.), *Everglades, The Ecosystem and Its Restoration*. St. Lucie Press, Delray Beach, Florida.
- BOSENCE, D. 1989. Surface sublittoral sediments of Florida Bay. *Bulletin of Marine Science* 44:434-453.
- BOTO, K. G. AND A. I. ROBERTSON. 1990. The relationship between nitrogen fixation and tidal exports of nitrogen in a tropical mangrove system. *Estuarine, Coastal and Shelf Science* 31:531-540.
- BULGER, A. J., B. P. HAYDEN, M. E. MONACO, D. M. NELSON, AND M. G. MCCORMICK-RAY. 1993. Biologically-based estuarine salinity zones derived from multivariate analysis. *Estuaries* 16:311-322.
- BUTLER, M. J. IV, J. V. HUNT, W. F. HERRNKIND, M. J. CHILDRESS, R. BERTELSON, W. SHARP, T. MATTHEWS, J. M. FIELD, AND H. G. MARSHALL. 1995. Cascading disturbances in Florida Bay, USA: Cyanobacteria blooms, sponge mortality, and implications for juvenile spiny lobsters, *Panulirus argus*. *Marine Ecology Progress Series* 129:119-125.
- CHRISTIAN, R. R., J. N. BOYER, D. W. STANLEY, AND W. M. RIZZO. 1991. Multi-year distribution patterns of nutrients in the Neuse River Estuary, North Carolina. *Marine Ecology Progress Series* 71:259-274.
- FOURQUREAN, J. W., G. V. N. POWELL, AND J. C. ZIEMAN. 1992a. Phosphorus limitation of primary production in Florida Bay: Evidence from the C:N:P ratios of the dominant seagrass, *Thalassia testudinum*. *Limnology and Oceanography* 37:162-171.
- FOURQUREAN, J. W., G. V. N. POWELL, AND J. C. ZIEMAN. 1992b. Relationships between porewater nutrients and seagrasses in a subtropical carbonate environment. *Marine Biology* 114:57-65.
- FOURQUREAN, J. W., R. D. JONES, AND J. C. ZIEMAN. 1993. Processes influencing water column nutrient characteristics and phosphorus limitation of phytoplankton biomass in Florida Bay, FL, USA: Inferences from spatial distributions. *Estuarine, Coastal and Shelf Science* 36:295-314.
- HARDIN, M. M., H. A. RINES, C. E. ROSE, AND M. B. ABEL. 1996. Spatial heterogeneity of macrophytes and selected invertebrates in Narragansett Bay (RI, USA) as revealed by principal component and cluster analyses. *Estuarine, Coastal and Shelf Science* 42:123-134.
- JACKILEE, J. B. AND D. R. HAMILTON. 1977. Objective analysis and classification of oceanographic data. *Tellus* 29:545-560.
- JONES, R. D., AND T. A. FRANKOVICH. In press. A rapid, precise, and sensitive method for the determination of total nitrogen in natural waters. *Marine Chemistry*.
- LAPOINTE, B. E. AND M. W. CLARK. 1992. Nutrient inputs from the watershed and coastal eutrophication in the Florida Keys. *Estuaries* 15:465-476.
- OVERLAND, J. E. AND R. W. PREISENDORFER. 1982. A significance test for principal components applied to cyclone climatology. *Monthly Weather Review* 110:1-4.
- PHILIPS, E. J. AND S. BADYLAK. 1996. Spatial variability in phytoplankton standing stock and composition in a shallow inner-shelf lagoon, Florida Bay, Florida. *Bulletin of Marine Science* 58:203-216.
- POWELL, G. V. N., W. J. KENWORTHY, AND J. W. FOURQUREAN. 1989. Experimental evidence for nutrient limitation of seagrass growth in a tropical estuary with restricted circulation. *Bulletin of Marine Science* 44:324-340.
- ROBBLEE, M. B., J. T. TILMANT, AND J. EMERSON. 1989. Quantitative observations on salinity. *Bulletin of Marine Science* 44:523.
- ROBBLEE, M. B., T. B. BARBER, P. R. CARLSON JR., M. J. DURAKO, J. W. FOURQUREAN, L. M. MUEHLSTEIN, D. PORTER, L. A. YABRO, R. T. ZIEMAN, AND J. C. ZIEMAN. 1991. Mass mortality of the tropical seagrass *Thalassia testudinum* in Florida Bay (USA). *Marine Ecology Progress Series* 71:297-299.
- SMITH, T. J. III, M. B. ROBBLEE, H. R. WANLESS, AND T. W. DOYLE. 1994. Mangroves, hurricanes, and lightning strikes. *BioScience* 44:256-262.
- SOLÓRZANO, L., AND J. H. SHARP. 1980. Determination of total dissolved phosphorus and particulate phosphorus in natural waters. *Limnology and Oceanography* 25:754-758.
- STRICKLAND, J. D. H., AND T. R. PARSONS. 1972. A practical handbook of seawater analysis. *Bulletin of the Fisheries Research Board of Canada* 167:107-112.
- TABB, D. C., D. L. DUBROW, AND R. B. MANNING. 1962. The ecology of northern Florida Bay and adjacent estuaries. Technical Series No. 39, Board of Conservation, State of Florida, Miami, Florida.
- THAYER, G. W., AND A. J. CHESTER. 1989. Distribution and abundance of fishes among basin and channel habitats in Florida Bay. *Bulletin of Marine Science* 44:200-219.
- TURNER, W. J., AND R. F. PERKINS. 1972. Molluscan distributions in Florida Bay. Sedimenta III, Comparative Sedimentology Laboratory, University of Miami, Florida.
- VANZELLA, A., M. A. GUERRERO, R. D. JONES. 1989. Effect of CO and light on ammonium and nitrite oxidation by chemolithotrophic bacteria. *Marine Ecology Progress Series* 57:69-76.

- VÉZINA, A. F., Y. GRATTON, AND P. VINET. 1995. Mesoscale physical-biological variability during a summer phytoplankton bloom in the lower St. Lawrence Estuary. *Estuarine, Coastal and Shelf Science* 41:393-411.
- ZIEMAN, J. C., J. W. FOURQUREAN, AND R. L. IVERSON. 1989. Dis-

tribution, abundance, and productivity of seagrasses and macroalgae in Florida Bay. *Bulletin of Marine Biology* 44:292-311.

Received for consideration, October 1, 1996

Accepted for publication, April 11, 1997

FLORIDA BAY: Temporal Analysis



Seasonal and long-term trends in the water quality of Florida Bay (1989-97)

JOSEPH N. BOYER¹

Southeast Environmental Research Program

Florida International University

Miami, FL 33199

JAMES W. FOURQUREAN

RONALD D. JONES

Southeast Environmental Research Program and

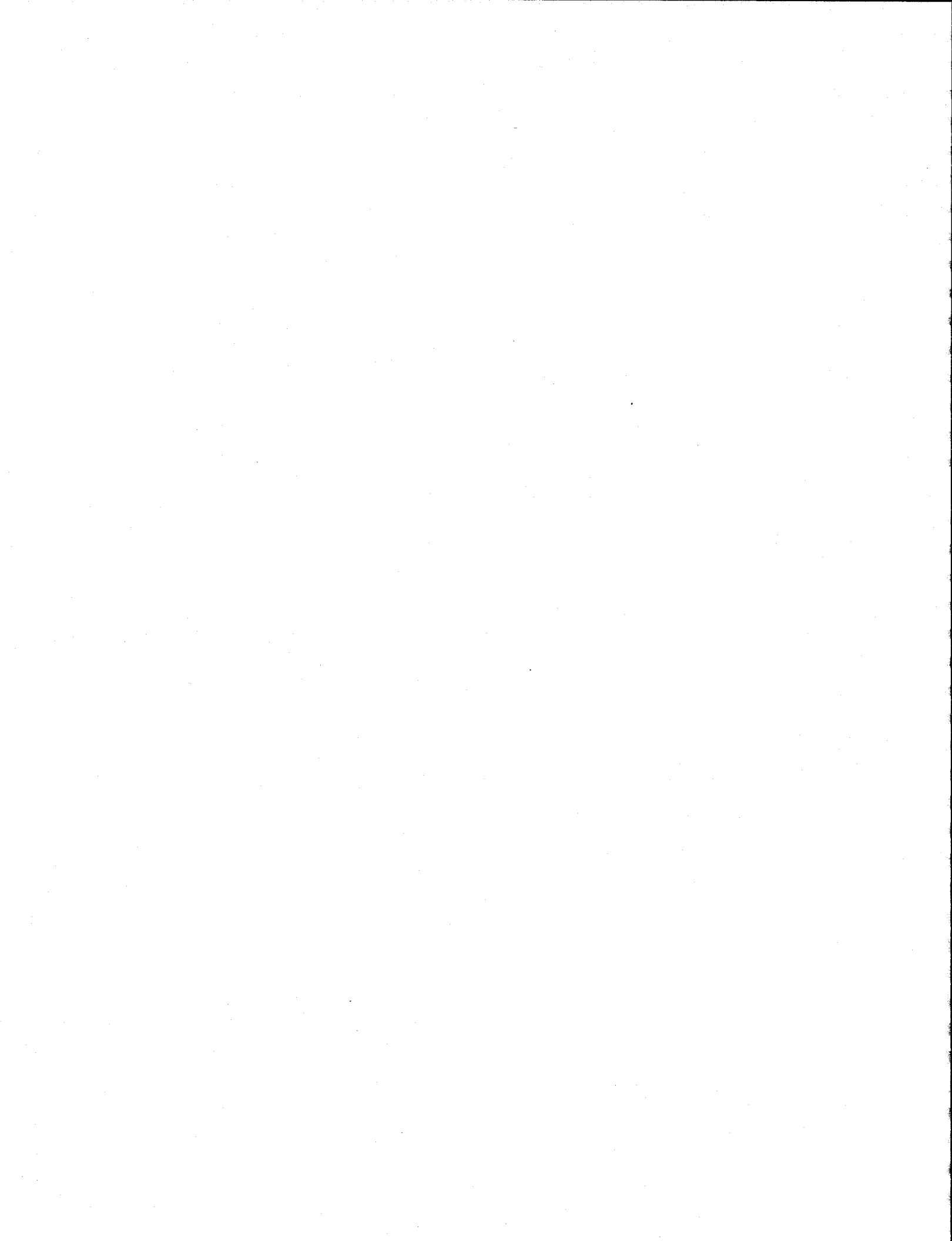
Department of Biological Sciences

Florida International University

Miami, FL 33199

¹Corresponding Author; tele: 305-348-4076; fax: 305-348-4096; boyerj@servax.fiu.edu

Draft of manuscript accepted for publication in [^]Estuaries (in press).



ABSTRACT: Analysis of 6 years of monthly water quality data was performed on 3 distinct zones of Florida Bay: Eastern Bay, Central Bay and Western Bay. Each zone was analyzed for trends at intra-annual (seasonal), interannual (oscillation), and long-term (monotonic) scales. Parameters such as TON, TOC, temperature, TN:TP ratio had seasonal maxima in the summer rainy season; indicators of the size and activity of the microplankton, APA and Chl *a*, tended to have maxima in the fall. In contrast, NO_3^- , NO_2^- , NH_4^+ , turbidity, and DO_{sat} were highest in the winter dry season. There were large changes in some of the water quality parameters of Florida Bay over the study period. Salinity and TP concentrations declined baywide while turbidity increased dramatically. The decline in salinity in Eastern, Central and Western Florida Bay was 13.6, 11.6, and 5.6 ppt, respectively. Some of this decrease in Eastern bay could be accounted for by increased freshwater flows from the Everglades. In contrast to most other estuarine systems, increased runoff may have been partially responsible for the decrease in TP concentrations as loading concentrations were $\sim 0.3 \mu\text{M}$. Turbidity in Eastern Bay increased 2-fold from 1991-96, while Central and Western Bays increased by factors of 20 and 4. Chl *a* concentrations were particularly dynamic and spatially heterogeneous. In the Eastern Bay, which makes up roughly half of the surface area of Florida Bay, Chl *a* declined by $0.9 \mu\text{g l}^{-1}$ (63%). The hydrographically isolated Central Bay zone underwent a 5-fold increase in phytoplankton biomass from 1989-94, then rapidly declined to 1989 levels. In Western Florida Bay, there was a significant increase in Chl *a*, yet median concentrations of Chl *a* in the water column remained modest ($\sim 2 \mu\text{g l}^{-1}$) by most estuarine standards. Only in Central Bay did the DIN pool increase substantially (3-6 fold). It important to note that these changes in turbidity and phytoplankton biomass happened after the poorly-understood seagrass dieoff in 1987; it is likely that the death and decomposition of large amounts of seagrass biomass can at least partially explain some of the changes in water quality of Florida Bay.

Introduction

One of the primary purposes for conducting long-term monitoring projects is to be able to detect trends in the measured parameters over time. These programs are usually initiated as a response to public perception (and possibly some scientific data) that "the river-bay-prairie-forest-etc. is dying". In the case of Florida Bay, the major impetus was the combination of a seagrass die-off (Robblee et al. 1991), increased phytoplankton abundance (Phlips and Badylak 1996), sponge mortality (Butler et al. 1995), and a perceived decline in fisheries (Tabb and Roessler 1989; Tilmant 1989) beginning in 1987. In response to these phenomena, a network of water quality monitoring stations was established in 1989 to explicate both spatial patterns and temporal trends in water quality in an effort to elucidate mechanisms behind the recent ecological change.

Previous analyses of Florida Bay water quality has shown that Florida Bay is a P limited marine ecosystem with a tendency towards hypersalinity (Fourqurean et al. 1993). A spatial analysis of 6 years of data from our monitoring program resulted in the delineation of 3 subsets of our monitoring stations which have robust similarities in water quality (Fig. 1; Boyer et al. 1997). We have argued that these spatially contiguous groups of stations are the result of similar loading and processing of materials, hence we call these groups "zones of similar influence" (ZSI).



The Eastern Bay ZSI acts most like a "conventional" estuary in that it has a quasi-longitudinal salinity gradient caused by the interaction of clearly definable seawater and freshwater endmembers. In contrast, the Central Bay is a hydrographically isolated area with low and infrequent terrestrial freshwater input, long water residence time, and high evaporative potential. The Western Bay ZSI is the most tidally influenced by the Gulf of Mexico and is also most isolated from direct overland freshwater sources.

Here we present time series analyses of monthly water quality data from these 3 composite ZSI of Florida Bay. There have indeed been significant changes in some water quality parameters in certain areas of Florida Bay that accompanied the other ecological changes taking place in the bay (i.e. seagrass dieoff, phytoplankton increases), but many parameters remained relatively unchanged.

Methods

SITE CHARACTERISTICS

Florida Bay is a wedge-shaped, shallow lagoonal estuary located off the southern tip of the Florida peninsula bounded by the Everglades to the north and open to the Gulf of Mexico along its western margin. The main line of the Florida Keys, a Pleistocene reef, separates Florida Bay from the Atlantic Ocean. The sediments of Florida Bay are composed mostly of biogenic carbonate muds (Bosence, 1989) so weathering of pre-existing substratum is not an important source of nutrients. Shallow mud banks divide Florida Bay into relatively discrete basins which restrict water mixing between basins and attenuate both tidal range and current. Florida Bay has a tropical savanna climate characterized by a long dry season and a wet season (Hela 1952). The dry season lasts from November-April, and generates only 18-33% of the annual total rainfall. The remainder of the annual precipitation falls during the May-October wet season (Schomer and Drew, 1982).

Freshwater flow in the Everglades ecosystem and therefore into Florida Bay is strongly manipulated by human activities (Light and Dineen 1994). Streamflow into Florida Bay is largely confined to two drainage areas: Taylor Slough and the C-111 basin. Taylor Slough is a natural watershed and flow route that historically drained the extreme SE Everglades. Water levels in Taylor Slough are modulated by the S175 control structure and the S332 pump station (Fig. 1). Flow in Taylor Slough is gaged downstream at the Taylor Slough bridge (TSB). The C-111 basin receives water from the controlled canal and levy system which regulates water levels in extreme south Florida. Freshwater flow into the C-111 basin is controlled at the S18C structure. Both the TSB and S18C are considerably upstream from the interface with Florida Bay, hence reported discharges should only be considered as rough approximations of freshwater inputs to Florida bay. See Fourqurean et al. (1997, this issue) for a more detailed description of the Florida Bay ecosystem.

SAMPLE COLLECTION AND ANALYSIS

A total of 28 sampling sites were distributed throughout Florida Bay (Fig. 1). Stations were sampled roughly every other month from July 1989 - Dec. 1990 and then monthly from Mar. 1991 to the present. Two consecutive days were required to complete each sampling event.



Surface salinity and temperature were measured using a combination salinity-conductivity-temperature probe (Orion model 140). Dissolved oxygen (DO, mg l^{-1}) was measured 10 cm below the surface using an oxygen electrode (Orion model 840) corrected for salinity and temperature. DO was converted to percent saturation (DO_{sat}) using the equations of García and Gordon (1992).

Duplicate water samples for dissolved nutrient analysis were collected from 10 cm below the surface using sample rinsed 150 ml syringes. Samples were filtered (25 mm Whatman GF/F) by hand into sample rinsed 60 ml HDPE bottles, which were capped and immediately placed on ice in the dark for transport. The wet filters, for chlorophyll *a* (Chl *a*) analysis, were placed in 1.8 ml plastic centrifuge tubes to which 1.5 ml of 90% acetone was added (Strickland and Parsons 1972); they were then capped and put into a dark bottle on ice for transport. Additionally, duplicate, unfiltered water samples were collected using sample rinsed 150 ml HDPE bottles and kept at ambient temperature in the dark during transport.

Unfiltered water samples were analyzed for total organic carbon (TOC), total nitrogen (TN), total phosphorus (TP), 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 $\text{pH} < 2$ 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 (Jones and Frankovich in press). TP was determined using a dry ashing, acid hydrolysis technique (Solórzano and Sharp 1980). The APA assay measures the activity of alkaline phosphatase, an enzyme produced by bacteria and algae which cleaves phosphate from organic compounds; we followed the method described in Boyer et al. (1997). Turbidity was measured using an HF Scientific model DRT-15C turbidimeter and reported in NTU.

Filtrates were analyzed for nitrate + nitrite (NO_x^-), nitrite (NO_2^-), ammonium (NH_4^+), and soluble reactive phosphorus (SRP) on a four channel autoanalyzer (Alpkem model RFA 300). Filters for Chl *a* content ($\mu\text{g l}^{-1}$) 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) with comparison to Chl *a* standards (Sigma). All analyses were completed within 3 weeks after collection.

Some parameters were not measured directly but were calculated by difference. Nitrate (NO_3^-) was calculated as $\text{NO}_x^- - \text{NO}_2^-$. Total inorganic nitrogen (TIN) was calculated as $\text{NO}_x^- + \text{NH}_4^+$. Total organic nitrogen (TON) was calculated as $\text{TN} - \text{TIN}$. All concentrations are reported as μM unless noted. The TN:TP ratio was calculated on a molar basis.

HYDROLOGIC DATA

Freshwater flow data ($\text{m}^3 \text{d}^{-1}$) from 1984-1996 was provided at gaging stations (S175, S332, TSB, and S18C) in Everglades National Park (ENP) operated by the South Florida Water Management District (SFWMD) and US Geological Service. All flow data was summed to get monthly and annual flow in $\text{Mm}^3 \text{yr}^{-1}$ ($10^6 \text{m}^3 \text{yr}^{-1}$). Precipitation data (cm d^{-1}) at the Royal Palm, Flamingo, and Tavernier monitoring sites (Fig. 1) were also obtained and summed to get monthly and annual inputs in cm yr^{-1} . We did not have any estimates of groundwater inputs to Florida Bay.

"ORGANIC" COMPONENT: TON, APA, AND TOC

The median concentration of TON in Central Bay ($80.8 \mu\text{M}$) was double that of Eastern and Western Bay (Table 1). There were significant differences in TON concentrations when the data were grouped by month in both Eastern Bay ($P < 0.001$) and Central Bay ($P = 0.001$), with maximum TON concentrations occurring in the summer (wet season) months (Fig. 2). In contrast, Western Bay did not display a significant seasonal cycle in TON ($P = 0.21$). The moving average for TON showed no evidence of interannual fluctuation in Eastern Bay (Fig. 2), but TON in Central Bay showed a rise during 1993-94 followed by a decline. The Western Bay MA showed some evidence of interannual oscillation on a 2 year period. The Kendall-t test showed no significant trend in TON for any of the ZSI (Table 1).

Median APA in the Central Bay was $5\times$ Eastern Bay and $8\times$ Western Bay (Table 1). APA showed season variation in all three zones. The APA in Eastern bay showed a modest increase in the fall months ($P = 0.013$, Fig. 3) while Central Bay was highly variable with lowest values in Mar.-May ($P = 0.003$). In Western Bay, the seasonal pattern in APA showed a dramatic increase from Oct.-Jan. ($P = 0.0001$). No interannual oscillation in APA was evident in Eastern Bay (Fig. 3). In Central Bay the MA increased linearly until 1994 when it then began to decline. The Kendall-t of Eastern Bay was negative indicating a decreasing trend in APA of $0.05 \mu\text{M hr}^{-1} \text{ yr}^{-1}$ (Table 1). No monotonic long-term trend was detected in the Central Bay because APA rose through 1991-93, then declined 1993-97. Some interannual oscillation in APA was seen in Western Bay (Fig. 3) but overall activity declined by $0.04 \mu\text{M hr}^{-1} \text{ yr}^{-1}$ (Table 1).

Median TOC in Central Bay ($1323 \mu\text{M}$) was more than twice as high as both Eastern and Western Bays (Table 1). There were no significant seasonal trends in TOC concentrations in Eastern and Western Bays (Fig. 4) but TOC in Central Bay was higher during May-Oct. ($P = 0.02$). The MA of TOC in Eastern and Western Bays showed a dip in 1993 with recovery by 1994 (Fig. 4). TOC in Central Bay increased over the period of record until mid 1994 when it also began to decline (Fig. 4). No significant trends in TOC for Florida Bay were evident (Table 1).

"DIN" COMPONENT: NO_2^- , NO_3^- , AND NH_4^+

Median NO_2^- concentration in Eastern Bay ($0.23 \mu\text{M}$) was almost twice as large as Central and Western Bay (Table 1). The seasonal pattern for NO_2^- for all ZSI was similar; NO_2^- concentration was highest during the cooler, dry season and lowest during the wet, hot season ($P < 0.0001$ for all, Fig. 5). The MA for Eastern Bay showed some evidence of a 2 year oscillation (Fig. 5) with no significant monotonic long-term trend (Table 1). The MA in Central Bay showed strong evidence of increasing NO_2^- concentration as well as increasing range (Fig. 5); the Kendall-t confirmed an increase of $0.06 \mu\text{M yr}^{-1}$. There was no long-term trend in NO_2^- concentration in Western Bay.

Median NO_3^- concentration in Eastern Bay was $\sim 3\times$ that of Central Bay and $6\times$ of Western Bay (Table 1). Seasonal patterns for NO_3^- among ZSI were similar to those for NO_2^- ($P < 0.0001$ for all, Fig. 6) with declines during the period from May-Sep. The MA for Eastern Bay showed some evidence of an oscillation (Fig. 6) but no long-term trend was noted (Table 1). The MA in Central Bay showed evidence similar to NO_2^- of increasing NO_3^- concentration and range (Fig. 6).

Central Bay had very high peaks in NH_4^+ concentration, up to 120 μM . The median was 7.3 μM which was 2x Eastern Bay and 7x that of Western Bay (Table 1). There were no seasonal patterns for NH_4^+ in Eastern and Western Bays but Central Bay showed a marked decline in concentration during May-Sep. (Fig. 7). The MA for Eastern Bay showed some evidence of a 2 year oscillating decline (Fig. 7) but the long-term downward trend was not significant ($P=0.29$). NH_4^+ concentration in Central Bay rose by 1.6 $\mu\text{M yr}^{-1}$ (Fig. 7, Table 1). Western Bay showed an increase in concentrations during 1993-94 which later declined to earlier levels. For this reason, there was no significant long-term trend.

"PHYTOPLANKTON" COMPONENT: TURBIDITY, TP AND CHL a

Highest median turbidity was found in both Central and Western Bays (8.6 and 7.2 NTU, respectively) with Eastern Bay being lowest (2.8 NTU). Turbidity was strongly seasonal across all of Florida Bay ($P<0.0001$), with maximum turbidities observed during the winter/spring when winds speeds are highest and generally from the NW (Fig. 8). Turbidity increased in all zones during the POR (Fig. 8) with the greatest increase in Central Bay (2.4 NTU yr^{-1}) followed by Western Bay (1.3 NTU yr^{-1}) and Eastern Bay (0.2 NTU yr^{-1} ; Table 1).

Median TP concentration was lower in the Eastern Bay (0.25 μM) than the Central and Western zones (Table 1). TP in all zones of Florida Bay showed no seasonal signal in concentration and little interannual fluctuation (Fig. 9). TP declined significantly in Eastern, Central and Western Bay at rates of 0.03-0.04 $\mu\text{M yr}^{-1}$ (Table 1).

Chl a concentrations in Eastern Bay were remarkably consistent (and low) over the annual cycle of wet and dry periods (Fig. 10), with the median being 0.96 $\mu\text{g l}^{-1}$. Chl a dropped precipitously in June 1994 and remained low for the remainder of the sampling period (Fig. 10). It should be noted that this type of discontinuity influenced the Kendall-t test by overestimating the TSE (Table 1), however, it is clear that Chl a concentrations have declined over this time period. Concentrations of Chl a in Central Bay were variable with lowest amounts found in early spring ($P=0.002$, Fig. 10). Chl a increased greatly from 1991-94 at an approximate rate of 1.0 $\mu\text{g l}^{-1} \text{yr}^{-1}$ (Fig. 10). It then began to decline at an equal rate until the present, leading us to conclude that there was no long-term trend in Chl a concentration in the Central Bay (Table 1). Concentrations of Chl a in Western Bay are usually highest during Oct.-Feb. coinciding with the cooler and windier dry season ($P<0.0001$, Fig. 10). Chl a increased in this zone at a rate of 0.12 $\mu\text{g l}^{-1} \text{yr}^{-1}$ (Fig. 10); a small amount relative to the median (1.93 $\mu\text{g l}^{-1}$) but nevertheless, significant ($P=0.065$, Table 1).

TEMPERATURE AND DO_{sat} COMPONENT

Water temperature in Eastern, Central, and Western Bay showed pronounced seasonal signals, as expected, but did not display any significant interannual trends (Fig. 11). Median temperature for all areas was ca. 26 °C. It is clear that the MA is effective at filtering out the seasonal signal in temperature. There were no significant long-term trends in temperature in any of the zones of Florida Bay (Table 1).

Intra-annual cycles of DO_{sat} were observed in all regions of Florida Bay (Fig. 12). The median DO_{sat} was 92.2, 86.3, and 88.8 % for Eastern, Central, and Western Bay respectively. Eastern Bay displayed a decreasing trend from May-Oct. with rapid recovery in Nov. This trend

was mirrored by Central and Western Bays but was more variable. The MA for all showed little interannual fluctuation in DO_{sat} in any of the ZSI (Fig. 12). There was no significant trend in DO_{sat} over the POR for any of the zones of Florida Bay (Table 1). It is interesting to note that the oxygen concentration in the water column was supersaturated with respect to air across Florida Bay during the sampling events prior to 1991. These data imply that there was a large decline in DO_{sat} during 1989-91 that remains to be explained.

SALINITY COMPONENT

Salinity in Eastern, Central and Western Bay showed evidence of a distinct seasonal patterns ($P < 0.0001$) with highest values occurring from Apr.-Sep., during the wet season (Fig. 13). The increase in salinity during the summer is caused by high summer evaporation rates and long water residence times in Florida Bay (Fourqurean et al. 1993). This seasonal pattern was more pronounced in the Central Bay where advective mixing is most restricted. In the Western Bay the seasonal signal in salinity was damped by open contact with the Gulf of Mexico.

The median salinity in Eastern Bay for the 6 yr POR was 28.1 ppt with the MA showing evidence of an interannual oscillation of ~ 2 yr periodicity (Fig. 13). In addition, there was a significant long-term decline of -2.3 ppt yr^{-1} or almost 14 ppt over the POR (Table 1). Median salinity in Central Bay was 34.1 ppt, and despite large interannual oscillations, declined significantly by almost 12 ppt over the POR ($TSE = -1.9$ ppt yr^{-1} , Table 1). In Western Bay, the MA showed less evidence of interannual oscillation due to Gulf of Mexico influence (Fig. 13) and the Kendall-t analysis showed a more modest decline in salinity of -0.9 ppt yr^{-1} (Table 1) or 5.5 ppt over the POR.

SRP

SRP was not included in any of the original principal components (Boyer et al. 1997) meaning it did not explain a significant amount of variance in the data. SRP concentrations are so low across Florida Bay (generally < 0.05 μM) as to be constrained by the analytical detection limit; consequently SRP does not explain a significant amount of the variance in the original data set (Boyer et al 1997). SRP in Eastern, Central, and Western Bay showed no seasonal change in concentration (Fig. 14). Little interannual oscillation was evident, however there were small but significant declines in SRP for all areas of Florida Bay (Table 1).

TN:TP RATIO

The TN:TP ratio in Eastern, Central and Western Bay showed some evidence of a seasonal pattern with higher values occurring in summer months and significant peaks in May. (Fig. 15). The median TN:TP in Eastern Bay was 184 (Table 1) but showed a sustained increase of 13 yr^{-1} ending at ~ 235 (Fig. 15). Median TN:TP in Central and Western Bays was 132 and 55.6, respectively with little interannual oscillation and no significant trends evident (Fig. 15).

HYDROLOGIC DATA

The S18C canal accounted for the largest proportion of potential overland freshwater flow, ranging from 70 – 412 Mm^3 yr^{-1} (Fig. 16). Losses and gains from groundwater between this structure and Florida bay are unquantified, so the actual amount of water entering Florida Bay

from this system is not known. However, due to its proximity to distribution, the ratio of actual freshwater input to S18C gage flow are probably closest to unity than for any of the other structures. S18C flow for the period 1990-95 (post 1989 drought) increased significantly by $38 \text{ Mm}^3 \text{ yr}^{-2}$ ($\tau=0.69$, $P=0.02$). Flows through the S175 fluctuated from lows of 8.3 and $3.6 \text{ Mm}^3 \text{ yr}^{-1}$ in 1989-91 to a high of $152 \text{ Mm}^3 \text{ yr}^{-1}$ in 1993. No trend in flow through the S175 was evident ($\tau=0.09$, $P=0.72$). The S332 flows prior to 1992 were $\sim 40 \text{ Mm}^3 \text{ yr}^{-1}$; from 1992 onward the flows increased dramatically up to $256 \text{ Mm}^3 \text{ yr}^{-1}$ in 1995 (Fig. 16). In addition there was a change in the S332 flow relative to the S18C. Prior to 1992, the S332 made up 19.7% of the combined flow; from 1992 on, the S332 contributed 33.2% of the total. This increase was also seen downstream of the S332 as a concurrent increase in flows at the TSB (Fig. 16). Annual TSB flows increased from an average of $20 \text{ Mm}^3 \text{ yr}^{-1}$ prior to 1992 to $73 \text{ Mm}^3 \text{ yr}^{-1}$ afterward.

Precipitation at Royal Palm, Flamingo, and Tavernier stations were used as a proxy of rainfall input to Florida Bay. Annual precipitation during 1989-96 ranged from 97-220 cm yr^{-1} (mean 136 cm yr^{-1}) for Royal Palm, 70-172 cm yr^{-1} (mean 110 cm yr^{-1}) for Flamingo, and 74-155 cm yr^{-1} (mean 111 cm yr^{-1}) for Tavernier (Fig. 16). No significant trend for this POR was observed at any of these sites.

Discussion

The water quality of Florida Bay, as described by the parameters measured in this monitoring network, is highly variable in both space and time. Classification of 28 sampling stations into 3 ZSI has allowed us to characterize trends in water quality parameters for broad regions of Florida Bay. This spatial scale is larger than that of the individual station but smaller than the whole ecosystem and is the result of statistical analysis and not arbitrary grouping. Our approach is justified by the heterogeneous nature of the system and the different water residence times therein (Boyer et al. 1997), and greatly simplifies the analysis of the data. In the temporal domain, we have analyzed for three scales of variability: intra-annual (seasonal), inter-annual (oscillations), and long-term monotonic trends.

Many of the measured parameters had seasonal maxima in the summer rainy season (Table 2). Obviously, water temperature followed a predictable pattern, with warmer temperatures in summer months, but concentrations of TON and TOC also tended to be greatest in the summer. This may be a result of enhanced decomposition of particulate organic matter in the warmer months or simply the concentration of solute by evaporation (salinity was also higher in the summer). Because of the lack of seasonality of TP and the fact that TON is the major component of TN, TN:TP ratios were also highest in the summer. Indicators of biomass and activity of the phytoplankton, Chl *a* and APA, tended to have maxima in the fall.

In contrast, some parameters were highest in the winter dry season, such as the DIN pool, turbidity, and DO_{sat} . It is unclear as to what drives this pattern in DIN but it is not due increased allochthonous loading from streamflow as this is the dry season. It is possible that the lower summer/fall concentrations are due to uptake by phytoplankton or it may be due to benthic remineralization as a result of seagrass senescence. Winds during this period are higher than the

rest of the year and generally come from the NE (Schomer and Drew 1992). Higher winds and the long fetch from this direction may result in more resuspension of the fine muds from the bottom of Florida Bay. The DO_{sat} maxima in winter and spring may be due to increased diffusion of oxygen across the air-water interface in the more turbulent and windy seasons, as well as there being less respiratory consumption of oxygen in the cooler months.

After removing the seasonal signal from the time series of water quality data, many aspects of water quality displayed directional change over the period of record of this data set (Table 3). Three parameters displayed the same long-term trend in all three ZSI: salinity, TP and SRP. Salinity declined in all sections of Florida Bay as a function of variations in climate: the beginning of our data collection coincided with the ending of a regional drought, and the years 1994-96 have all been wetter than normal, but no statistically significant trend was evident. Fresh water enters Florida Bay as rainfall, surface water runoff and groundwater; more rainfall has led to a general increase in the surface water inputs since 1987 (Fig. 16). Regression of detrended monthly precipitation and combined monthly flows (S18C + TSB) was significant ($P < 0.01$) but explained $< 2\%$ of the variance, supplying very little predictive power for any type of modeling effort. Full scale prediction of salinities in Florida Bay will require a more detailed assessment of inputs and mixing across Florida Bay

Freshwater entering Florida Bay from overland sources has a lower TP concentration than seawater entering Florida Bay from the Gulf of Mexico (Fourqurean et al. 1993; Boyer and Jones submitted) and from precipitation ($0.15-0.30 \mu M$; R. Jones unpublished data). This may help to explain some of the decline in P concentrations in the Bay but without process rate measurements we can only speculate as to the cause.

Other water quality parameters had different long-term trends in the different zones (e.g. Chl a , Table 3). These regional differences are the result of the varying importance of freshwater runoff, oceanic exchange, and internal processing of nutrients across Florida Bay and are discussed below.

EASTERN FLORIDA BAY

Eastern Bay is most influenced by freshwater inputs from land, specifically Taylor Slough and the C-111 basin. Salinity in Eastern Florida Bay showed a 38% decline over the POR (Table 3). This was most probably due to increased freshwater flows and rainfall as a result of both climatic factors (alleviation of drought) and management efforts (increased flows to Taylor Slough). Boyer and Jones (submitted) reported that annual median salinity of Eastern Bay was correlated to freshwater inputs ($r^2 = 0.85$, $P = 0.001$).

Concurrent with increased freshwater inputs was a 51% decrease in TP and a 22% decrease in SRP concentrations (Table 3). This type of trend is contrary to observations from most estuarine ecosystems where increased runoff causes greater loading and therefore, higher nutrient concentrations. While TP loading did increase with flow, the TP concentration of the incoming water ($0.30 \mu M$) did not change significantly (Boyer and Jones submitted). This means that the trend of decreasing TP concentrations in Eastern Florida Bay may have been due simply to dilution by increased freshwater inputs. SRP concentrations are usually at or near detection limits, so a significant decline over the POR was unexpected. It follows that decreases in TP should also be reflected in SRP concentrations as well. Greater sediment absorption with

decreased salinity could possibly account for this decline but has not been quantified. It is interesting to note that the increased turbidity caused by resuspension of bottom sediments over the period 1989-1997 did not result in increased SRP concentrations in the water column. Another response to the decrease in TP was an increase in the TN:TP ratio of the system (Table 1). We emphasize that the high TN:TP ratio of Eastern Florida Bay is due to the extremely low concentrations of TP in the system and not to increased or high concentrations of N.

Concurrent with the decrease in salinity, TP, and SRP in Eastern Florida Bay was a loss of density of the seagrass Halodule wrightii (Hall et al. 1997, this volume). Light penetration of the water column, which often controls seagrass density (e.g. Dennison, 1987), decreased slightly in eastern Florida Bay over this interval (turbidity increased by 1.3 NTU over the POR, Table 3). It is unlikely that this increase in turbidity caused the observed decline in H. wrightii density because there was no concurrent decline in the dominant seagrass of the region, Thalassia testudinum (Hall et al. 1997, this volume). There is a possible connection between decreased P in the water column and the loss of H. wrightii as this species has a higher demand for nutrients than T. testudinum (Fourqurean et al 1992, 1995) and is therefore more restricted to areas of higher nutrient availability. Powell et al. (1989) speculated that historic (pre-1984) declines in the prevalence of H. wrightii in eastern Florida Bay (documented in Schmidt 1979 and Zieman 1982) were caused by a decrease in P loading from the Everglades watershed caused by a decrease in the amount of freshwater entering the bay via streamflow. This work suggests the opposite: as freshwater inflow increased over the period 1989-97, TP and SRP concentrations in the water column decreased. Perhaps this decrease in water column P availability led to the decline in H. wrightii abundance over the same period.

Chl a concentrations decreased in Eastern Florida Bay by 63% (Table 3). We believe the decline in phytoplankton biomass during this period is further evidence of the P limited nature of this zone (Fourqurean et al. 1993, Philips and Badylak, 1996). With the decline in TP concentrations we expected to see an increase in APA as the bacteria and algae produced more exoenzyme to alleviate P limitation, but the reverse was true; APA declined by 52% (Table 3). As we do not have data on bacterial numbers, we can not determine whether the APA decline was due to a decrease in the bacterial population, a shift in community structure, or a decrease in cell-specific enzyme production. However, some algae and most cyanobacteria do produce alkaline phosphatase so the decline in APA may be due to the observed general decline in phytoplankton biomass.

WESTERN BAY

The trends in Western Bay were similar to those of Eastern Bay with the exception of Chl a. Salinity declined by 5 ppt over the POR while TP, SRP, and APA declined by 34, 63, and 58% overall (Table 3). The salinity decline may have been partially due to increased freshwater flows in the Eastern Bay but was more likely the result of a freshening of the waters of the SW Florida Shelf from Shark Slough drainage, and the influence of increased rainfall. There is increasing evidence that inshore shelf waters become entrained with Gulf of Mexico waters flowing south through Western Florida Bay and out to the Atlantic Ocean through passes in the Keys (Smith

1994; T. Lee pers. com.). This mixing of low P waters from Shark Slough with Gulf of Mexico might also explain the reduction in P concentrations as well.

Turbidity in the Western Bay ZSI increased four-fold between 1989 and 1991 (Table 3), probably as a result of resuspension of the bottom sediments that had become destabilized by the seagrass die-off that began in 1987 (Robblee et al. 1991; Hall et al. 1997, this volume; Zieman et al. 1997, this volume). As in Eastern Bay, increased benthic resuspension of carbonate sediments did not lead to an increase of P concentrations in the water column; in fact, concentrations of both TP and SRP declined over the study period. Concurrent with the decline in water-column P, Chl *a* concentrations did increase in this zone by $0.7 \mu\text{g l}^{-1}$. This observation suggests that the water column in the Western Bay ZSI is not as strongly limited by P as Central and Eastern Bays.

CENTRAL BAY

Salinity, TP, and SRP in Central Bay all decreased over the POR in the Central Bay ZSI (Table 3). Salinity declined by 28%, likely due to the regional climatic factors that influenced rainfall and runoff into Florida Bay. TP declined by $0.21 \mu\text{M}$ (Table 3), a drop of 28%; while SRP declined by $0.05 \mu\text{M}$, a 66% decline. There was no long term monotonic trend in Chl *a* for the POR but this is misleading. During 1991-94, median Chl *a* increased by a factor of 4 but then declined to previous levels by 1996.

The Central Bay was the zone most strongly affected by the seagrass dieoff (Robblee et al. 1991); over 4000 ha were lost between 1987-88 yet the increase in phytoplankton biomass and decrease in light penetration of the water column did not begin until 1991 (Figure 10). We can only speculate as to why it took 3 years for increases in phytoplankton biomass to occur. Perhaps hypersaline conditions kept phytoplankton growth in check following the loss of seagrass until 1991. It is unfortunate that no P or Chl *a* data exist for Florida Bay for the period of active seagrass dieoff, but it was remarkable how optically clear the waters were overlying the dying seagrass beds (10 m visibility, J. W. Fourqurean, personal observations).

In contrast to the rest of Florida Bay, DIN concentrations in Central Bay showed significantly increasing trends (Table 3). Both NO_2 and NO_3 concentrations tripled while NH_4 increased six-fold with largest increases occurring after 1994. These increases may be due to remineralized N from decaying seagrass belowground biomass. We also observed an interannual oscillation in NH_4 during 1992-94 that coincided with the large increase in Chl *a* (Figs. 7 and 10). It is quite possible that the 1992-94 drawdown was a result of phytoplankton N demand. If this is the case, we do not understand why there is no such response in the TP or SRP pools (Figs. 9 and 14).

There are 5 possible sources of N to Florida Bay: advective mixing, N_2 -fixation, terrestrial runoff, groundwater input, and precipitation. In the case of Central Florida Bay, transport in by advective mixing is restricted by the western banks resulting in long water residence times. N_2 -fixation has been shown to be a significant source of N to seagrass in Biscayne Bay (Capone and Taylor 1980); porewater and seagrass measurements led Fourqurean et al. (1992) to speculate that N_2 -fixation may be an important N source for the Central Bay. The importance of N_2 -fixation may also have increased due to the recent (post 1991) presence of cyanobacterial blooms in this region (Phlips and Badylak, 1996). Nitrogen loading from land runoff in this area is low

and probably not significant. Groundwater input is unknown. Precipitation in this region is high in the summer months but probably does not get more rainfall than the rest of Florida Bay.

There are only 3 significant sinks for N in this ecosystem: advection, burial, and denitrification. As previously mentioned, advective mixing is low. Burial of N is a significant sink but total N concentrations in deeper sediments is not excessive (P. Carlson, pers. com.). Denitrification has been shown to be a significant sink of N in most other estuaries and with relatively high and increasing NO_3^- and TOC concentrations in the Central Bay we would not expect denitrification to be N or C limited. Apparently, over the period 1989-96 the sources of N to the water column of Central Bay increased in relation to the sinks.

Conclusions

Rapid environmental changes have precipitated a general concern for the state of the Florida Bay ecosystem. It is clear there have been major changes in some water quality parameters of Florida Bay over the study period. Salinity and P concentrations have declined baywide while turbidity has increased dramatically. In contrast to most other estuarine systems, increased runoff from the watershed may have actually decreased the concentration of P, the limiting nutrient, in the water column. Chl *a* concentrations were particularly dynamic in Florida Bay, but these dynamics were spatially heterogeneous. In the Eastern Bay zone, which makes up roughly half of the surface area of Florida Bay, phytoplankton abundance has significantly declined. The hydrographically isolated Central Bay zone underwent a 5-fold increase in phytoplankton abundance from 1989-94; but then rapidly declined to 1989 levels. In Western Florida Bay, there was a significant rise in phytoplankton abundance, yet median concentrations of Chl *a* in the water column remain modest ($\sim 2 \mu\text{g l}^{-1}$) by most estuarine standards. The major factor contributing to the anecdotal stories of decreased water clarity in Florida Bay since 1991 are apparently fueled by an increase in non-phytoplankton turbidity. Turbidity in Western Bay increased 4-fold from 1991-96; while turbidity in Central Bay increased by a factor of 20. It is important to note that these changes in turbidity and phytoplankton abundance happened after the poorly-understood seagrass dieoff in 1987; it is likely that the death and decomposition of large amounts of seagrass biomass can at least partially explain some of the changes in water quality of Florida Bay. Finally, future management strategy based on this trend analysis must be placed in context with historical behavior: six years of data is a narrow window of time relative to the natural cycling of the ecosystem.

ACKNOWLEDGMENTS

We thank Pete Lorenzo, Tom Frankovich, Jeff Absten, and all the other field and laboratory technicians involved with this project over the years. This study was supported by the South Florida Water Management District (C-7919) and Everglades National Park (CA5280-2-9017). This is contribution #xx of the Southeast Environmental Research Program at Florida International University.

LITERATURE CITED

- BOYER, J. N., J. W. FOURQUREAN, AND R. D. JONES. 1997. Spatial characterization of water quality in Florida Bay and Whitewater Bay by multivariate analysis: Zones of similar influence (ZSI). Estuaries 20:743-758.
- BUTLER, M. J. IV, J. H. HUNT, W. F. HERRNKIND, AND OTHERS. 1995. Cascading disturbances in Florida Bay, USA: cyanobacteria blooms, sponge mortality, and implications for juvenile spiny lobsters Panulirus argus. Marine Ecology Progress Series 129:119-125.
- CAPONE, D. G. AND B. F. TAYLOR. 1980. Microbial nitrogen cycling in a seagrass community, p. 153-161. In V. S. Kennedy (ed.), Estuarine perspectives. Academic.
- CHATFIELD, C. 1989. The analysis of time series. Chapman & Hall.
- CHRÓST, R. J. 1990. Microbial ectoenzymes in aquatic environments, p. 47. In J. Overbeck and R. J. Chróst (eds.), Aquatic microbial ecology: biochemical and molecular approaches. Springer-Verlag.
- DENNISON, W. C. 1987. Effects of light on seagrass photosynthesis, growth and depth distributions. Aquatic Botany 27:15-26.
- FOURQUREAN, J. W., R. D. JONES, AND J. C. ZIEMAN. 1993. Processes influencing water column nutrient characteristics and phosphorus limitation of phytoplankton biomass in Florida Bay, FL, USA: Inferences from spatial distributions. Estuarine, Coastal Shelf Science 36:295-314.
- FOURQUREAN, J. W., G. V. N. POWELL, AND J. C. ZIEMAN. 1992. Relationships between porewater nutrients and seagrasses in a subtropical carbonate environment. Marine Biology 114:57-65.
- FOURQUREAN, J. W., G. V. N. POWELL, W. J. KENWORTHY, AND J. C. ZIEMAN. 1995. The effects of long-term manipulation of nutrient supply on competition between the seagrasses Thalassia testudinum and Halodule wrightii in Florida Bay. Oikos 72:349-358.
- GARCÍA, H. E., AND L. I. GORDON. 1992. Oxygen solubility in seawater: Better fitting equations. Limnology and Oceanography 37:1307-1312.
- HELA, J. 1952. Remarks on the climate of southern Florida. Bulletin of Marine Science 2:438-447.
- HIRSCH, R. M., R. B. ALEXANDER, AND R. A. SMITH. 1991. Selection of methods for the detection and estimation of trends in water quality. Water Resources Research 27: 803-813.
- JONES, R. D., AND T. A. FRANKOVICH. 1998. A rapid, precise, and sensitive method for the determination of total nitrogen in natural waters. Marine Chemistry (in press).
- LIGHT, S. S., AND J. W. DINEEN. 1994. Water control in the Everglades: a historical perspective, p. . In S. M. Davis and J. C. Ogden (eds.), Everglades: the ecosystem and its restoration. St. Lucie Press.
- MCGILL, R., J. W. TUKEY, AND W. A. LARSEN. 1978. Variations of box plots. American Statistician 32:12-16.

- PHILIPS, E. J. AND S. BADYLAK. 1996. Spatial variability in phytoplankton standing crop and composition in a shallow inner-shelf lagoon, Florida Bay, Florida. Bulletin of Marine Science 58:203-216.
- ROBBLEE, M. B., J. T. TILMANT, AND J. EMERSON. 1989. Quantitative observations on salinity. Bulletin of Marine Science 44:523.
- SCHMIDT, T. W. 1979. Ecological study of the fishes and the water quality characteristics of Florida Bay, Everglades National Park, Florida. U. S. National Park Service, Everglades National Park, Homestead, FL. 145 pp.
- SCHOMER, N. S. AND R. D. DREW. 1982. An ecological classification of the lower Everglades, Florida Bay and the Florida Keys. FWS/OBS-82/58.1. Washington, DC. 246 pp.
- SMITH, N. 1994. Long-term Gulf-to-Atlantic transport through tidal channels in the Florida Keys. Bulletin of Marine Science 54:602-609.
- SOLÓRZANO, L., AND J. H. SHARP. 1980. Determination of total dissolved phosphorus and particulate phosphorus in natural waters. Limnology and Oceanography 25:754-758.
- TABB, D. C., AND M. A. ROESSLER. 1989. History of studies on juvenile fishes of coastal waters of Everglades National Park. Bulletin of Marine Science 44:23-34.
- TILMANT, J. T. 1989. A history and an overview of recent trends in the fisheries of Florida Bay. Bulletin of Marine Science 44:3-22.
- ZIEMAN, J. C. 1982. The ecology of seagrasses of south Florida: a community profile. FWS/OBS-82/25, Washington, DC. 158 pp.

FIGURE LEGENDS

Fig. 1. Map of zones of similar influence (ZSI) as a result of cluster analysis on mean and SD of five principal component scores. Stations as labeled are: Eastern Bay (+), Central Bay (■), and Western Bay (●).

Fig. 2. Box-and-whisker and time series plots of TON (μM) by ZSI. Box-and-whisker plots include all monthly data for 19 stations in Eastern Bay, 4 stations in Central Bay, and 6 stations in Western Bay for 1991-97. The center horizontal line in 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. Outliers were omitted from all graphs to reduce compression. For time series plots, the open circles are medians of all stations in each ZSI for each month sampled. The heavy smoothed line is the centered 12-month moving average (MA) of the data. The closed circles are discontinuous data collected prior to Mar. 1991 which were not included in the analyses; they are reported only for comparative purposes.

Fig. 3. Box-and-whisker and time series plots of APA ($\mu\text{M hr}^{-1}$) by ZSI.

Fig. 4. Box-and-whisker and time series plots of TOC (μM) by ZSI.

Fig. 5. Box-and-whisker and time series plots of NO_2^- (μM) by ZSI.

Fig. 6. Box-and-whisker and time series plots of NO_3^- (μM) by ZSI.

Fig. 7. Box-and-whisker and time series plots of NH_4^+ (μM) by ZSI.

Fig. 8. Box-and-whisker and time series plots of turbidity (NTU) by ZSI.

Fig. 9. Box-and-whisker and time series plots of TP (μM) by ZSI

Fig. 10. Box-and-whisker and time series plots of Chl a ($\mu\text{g l}^{-1}$) by ZSI

Fig. 11. Box-and-whisker and time series plots of temperature ($^{\circ}\text{C}$) by ZSI.

Fig. 12. Box-and-whisker and time series plots of DO_{sat} (%) by ZSI.

Fig. 13. Box-and-whisker and time series plots of salinity (ppt) by ZSI.

Fig. 14. Box-and-whisker and time series plots of SRP (μM) by ZSI.

Fig. 15. Box-and-whisker and time series plots of TN:TP by ZSI.

Fig. 16. Annual freshwater flows ($\text{Mm}^{-3} \text{ yr}^{-1}$) at individual water control structures in the Everglades for 1989-96. Annual precipitation records (cm yr^{-1}) for rain gages at Royal Palm, Flamingo, and Tavernier.

Table 1. Median values of all parameters for the period of record are shown for each zone. Results of seasonal Kendall- τ test are reported as median, τ value, significance of trend (P), and trend slope estimate (TSE) in units yr^{-1} .

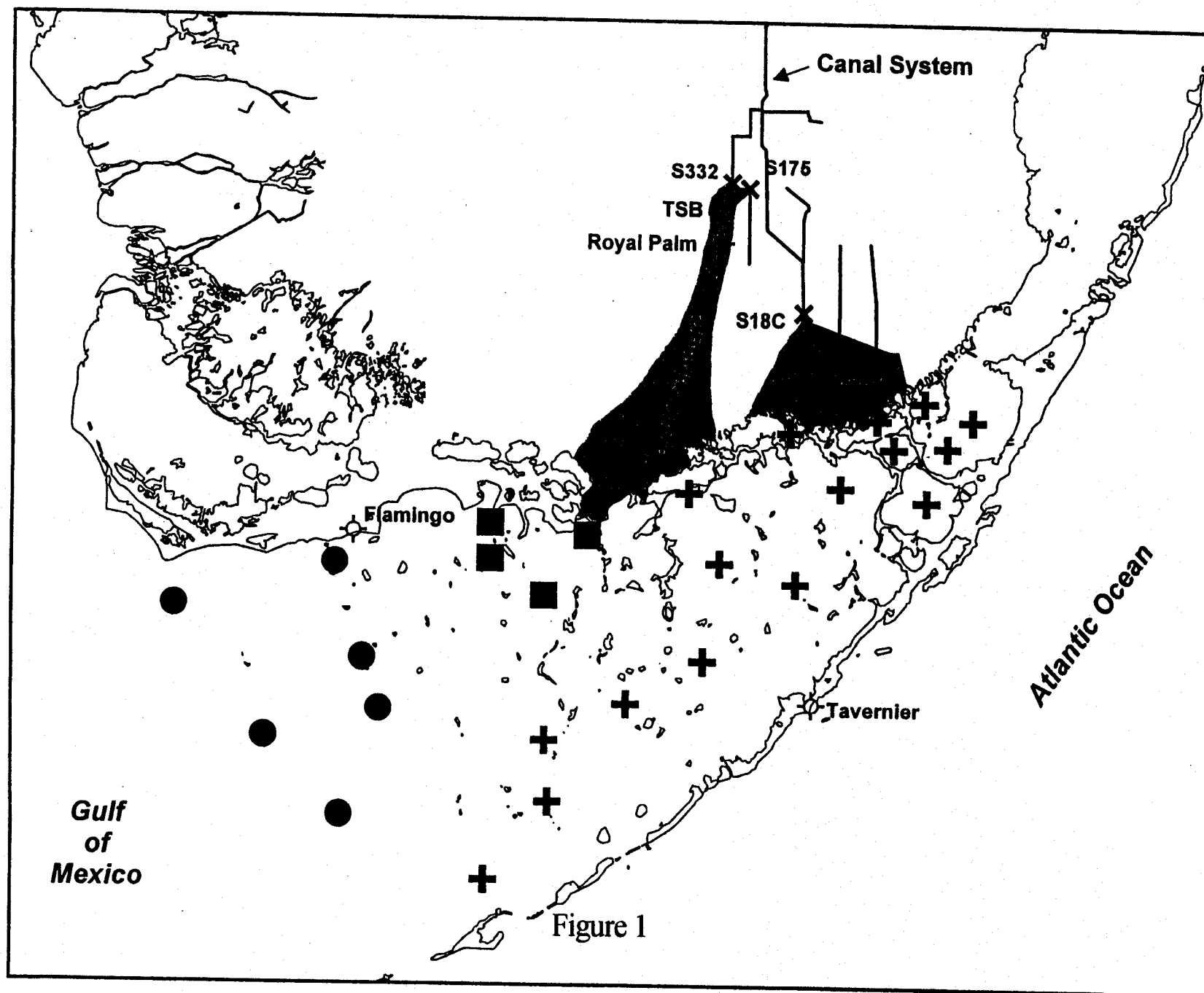
Parameter	Eastern Bay				Central Bay				Western Bay			
	Median	τ	P	TSE	Median	τ	P	TSE	Median	τ	P	TSE
TON (μM)	46.0	-0.21	0.2530	-0.790	80.8	-0.24	0.1872	-4.212	30.5	0.12	0.5382	0.385
APA ($\mu\text{M hr}^{-1}$)	0.40	-0.56	0.0015	-0.050	1.95	-0.18	0.3334	-0.127	0.24	-0.39	0.0279	-0.035
TOC (μM)	695.9	-0.21	0.2530	-11.52	1323	-0.12	0.5382	-32.86	439.9	0.03	0.9299	4.764
NO_2^- (μM)	0.23	-0.06	0.7903	-0.006	0.15	0.77	0.0000	0.055	0.11	0.05	0.8599	0.002
NO_3^- (μM)	0.71	0.14	0.4801	0.008	0.26	0.62	0.0003	0.109	0.12	-0.03	0.9294	0.000
NH_4^+ (μM)	3.41	-0.29	0.1121	-0.319	7.27	0.42	0.0176	1.558	1.05	-0.11	0.5964	-0.065
Turbidity (NTU)	2.84	0.35	0.0521	0.222	8.56	0.64	0.0003	2.451	7.18	0.61	0.0006	1.320
TP (μM)	0.25	0.56	0.0012	-0.030	0.65	-0.36	0.0415	-0.036	0.58	-0.33	0.0648	-0.041
Chl <i>a</i> ($\mu\text{g l}^{-1}$)	0.85	-0.74	0.0000	-0.143	2.34	-0.03	0.9299	-0.012	1.93	0.33	0.0648	0.118
DO_{sat} (%)	92.2	0.03	0.9299	0.048	86.3	0.12	0.5382	1.003	88.8	0.18	0.3334	0.566
Temp. ($^{\circ}\text{C}$)	25.8	0.12	0.5350	0.100	25.6	0.08	0.7240	0.071	25.6	-0.06	0.7919	-0.088
Salinity (ppt)	28.1	-0.56	0.0015	-2.267	34.1	0.42	0.0167	-1.943	35.2	-0.39	0.0279	-0.925
SRP (μM)	0.03	-0.27	0.0998	-0.001	0.05	-0.52	0.0030	-0.009	0.03	-0.53	0.0019	-0.005
TN:TP	184.4	0.52	0.0037	13.01	131.9	0.18	0.3334	7.033	55.6	0.21	0.2530	2.369

Table 2. Seasonal highs in water quality parameters from Kruskal-Wallace test ($P < 0.1$) for period of record 1991-1997.

Parameter	Eastern Bay	Central Bay	Western Bay
TON	Summer	Summer	
APA	Fall	Fall	Winter
TOC		Summer	
NO ₂ ⁻	Winter	Winter	Winter
NO ₃ ⁻	Winter	Winter	Winter
NH ₄ ⁺		Winter	
Turbidity	Winter/Spring	Winter/Spring	Winter/Spring
TP			
Chl <i>a</i>		Fall	Fall/Winter
Temperature	Summer	Summer	Summer
DO _{sat}	Winter/Spring	Winter/Spring	Winter/Spring
Salinity	Summer	Summer	Summer
SRP			
TN:TP	Summer	Summer	Summer

Table 3. Significant trends ($P < 0.10$) in water quality parameters from Kendall- τ test for period of record 1991-1997.

Parameter	Eastern Bay	Central Bay	Western Bay
	Change	Change	Change
Salinity (ppt)	↓ 13.6 (-38%)	↓ 11.6 (-28%)	↓ 5.6 (-15%)
TP (μM)	↓ 0.18 (-51%)	↓ 0.21 (-28%)	↓ 0.25 (-34%)
Chl a ($\mu\text{g l}^{-1}$)	↓ 0.86 (-63%)		↑ 0.71 (1.5x)
Turbidity (NTU)	↑ 1.3 (1.6x)	↑ 14.7 (20x)	↑ 7.9 (4x)
SRP (μM)	↓ 0.01 (-22%)	↓ 0.05 (-66%)	↓ 0.03 (-63%)
APA ($\mu\text{M hr}^{-1}$)	↓ 0.30 (-52%)		↓ 0.21 (-58%)
NO_2^- (μM)		↑ 0.33 (3x)	
NO_3^- (μM)		↑ 0.65 (2.8x)	
NH_4^+ (μM)		↑ 9.4 (6x)	
TN:TP	↑ 78 (1.5x)		



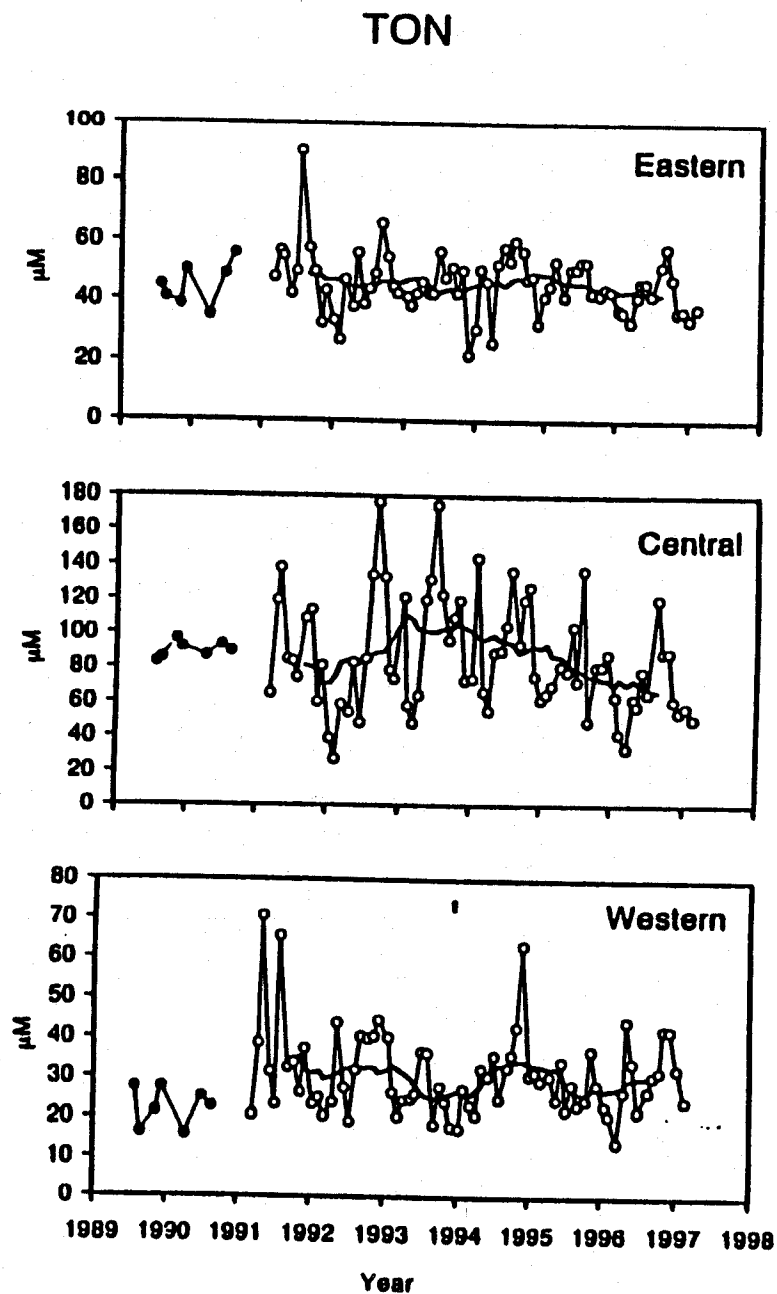
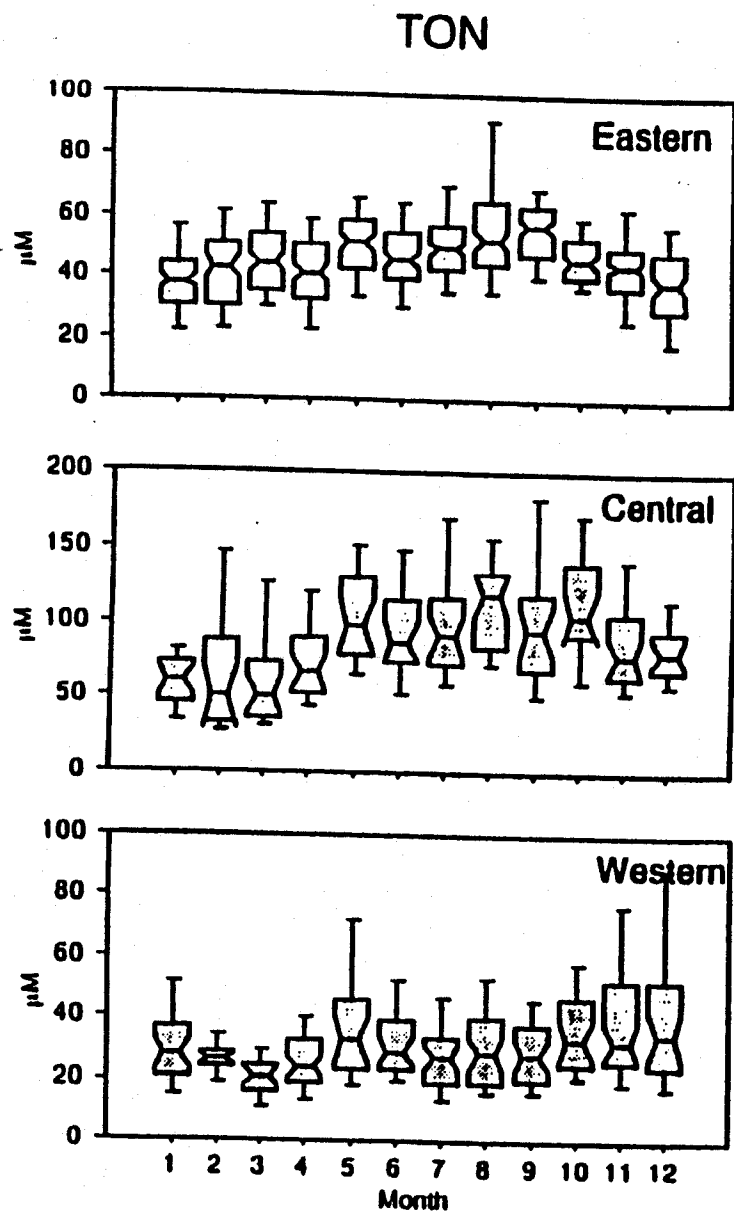


Figure 2

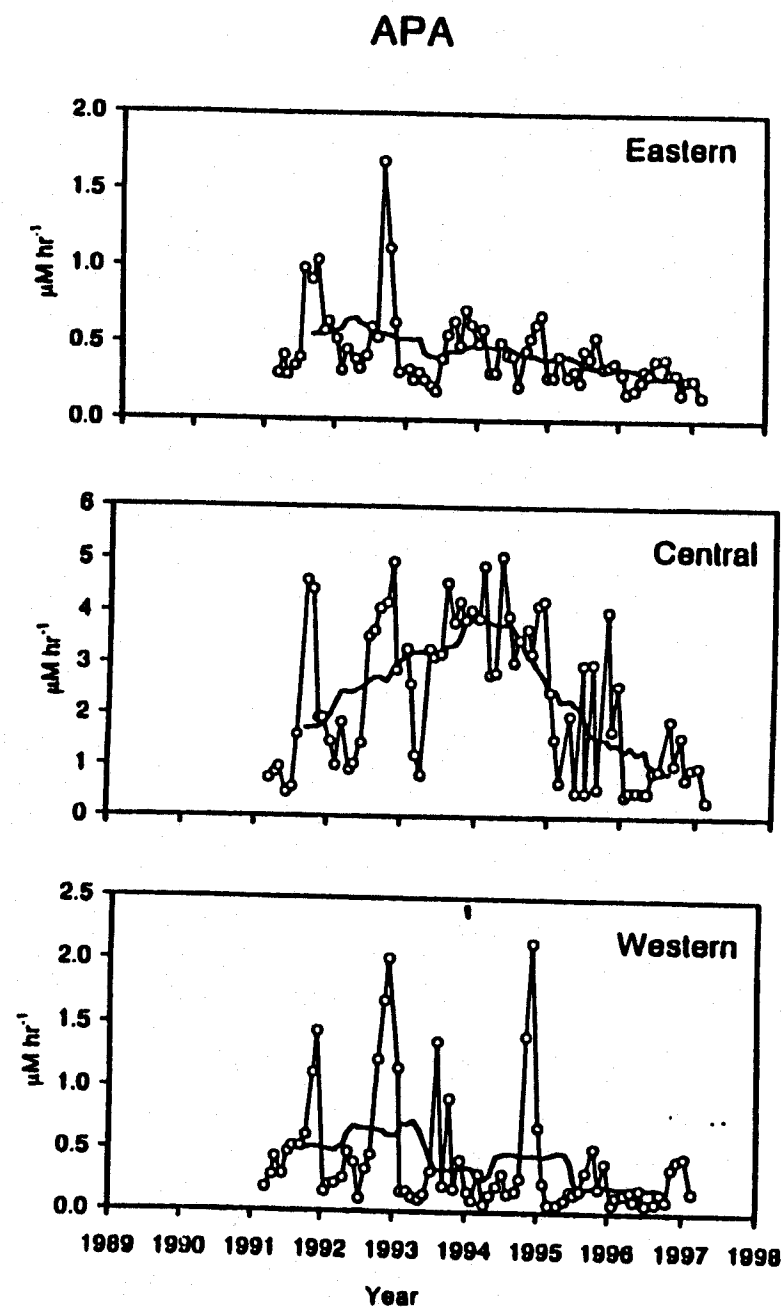
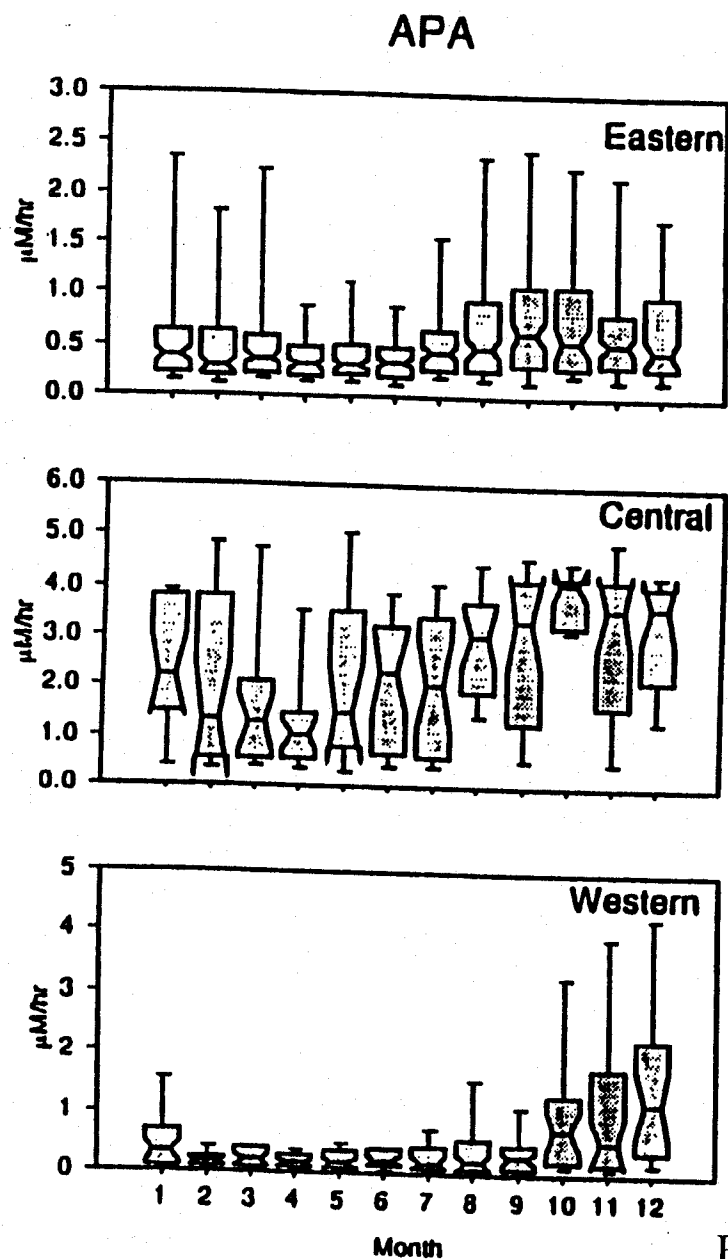


Figure 3

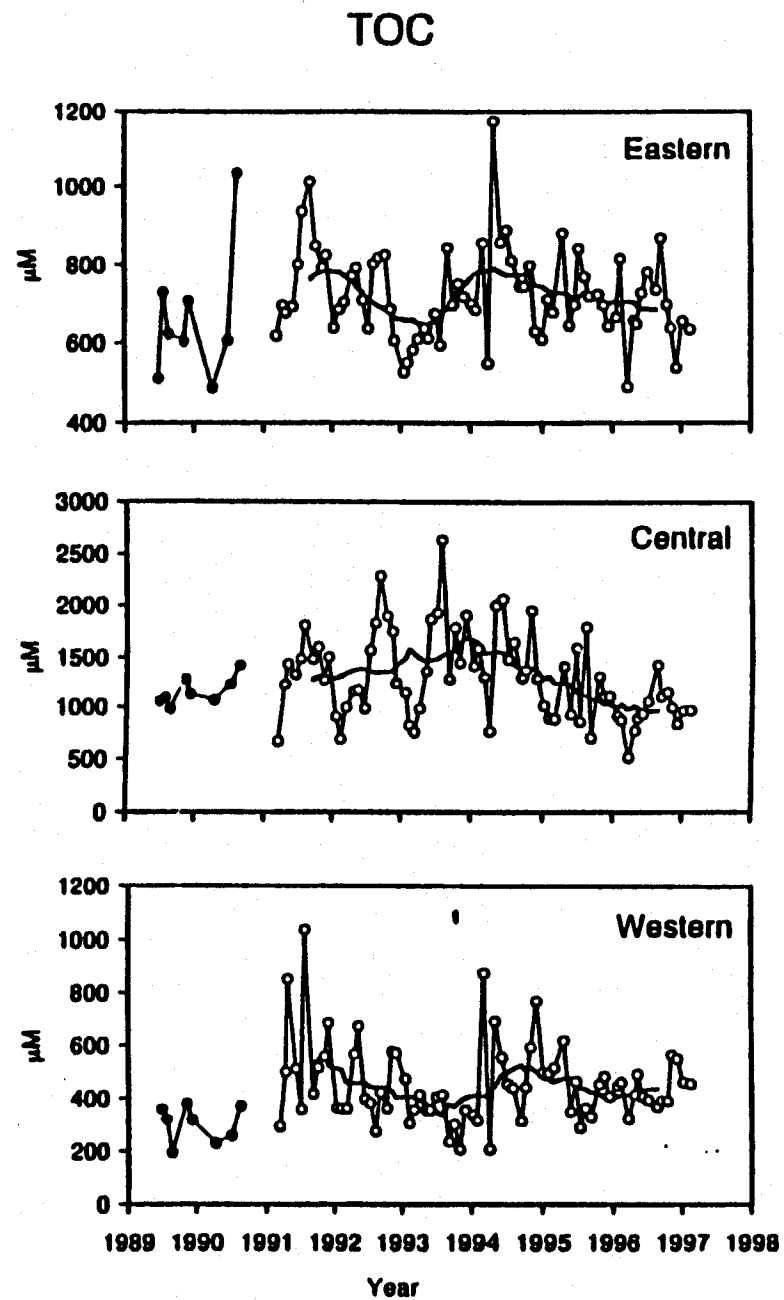
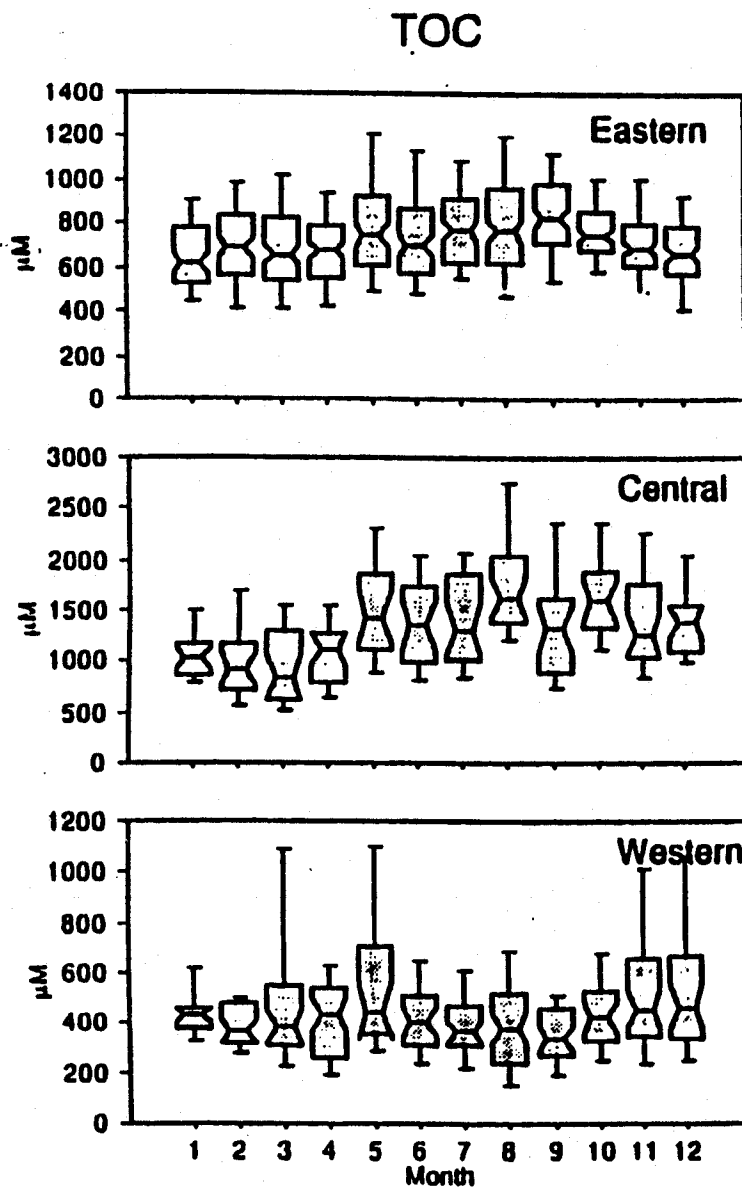


Figure 4

NO₂

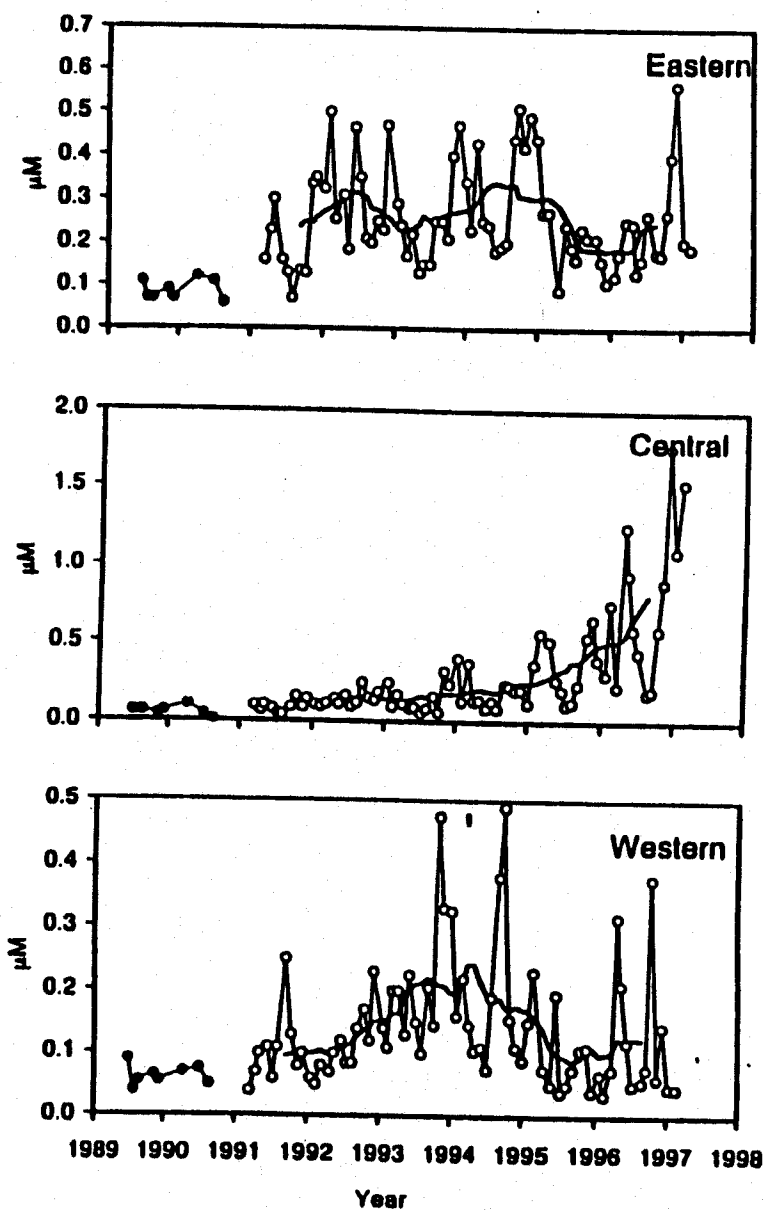
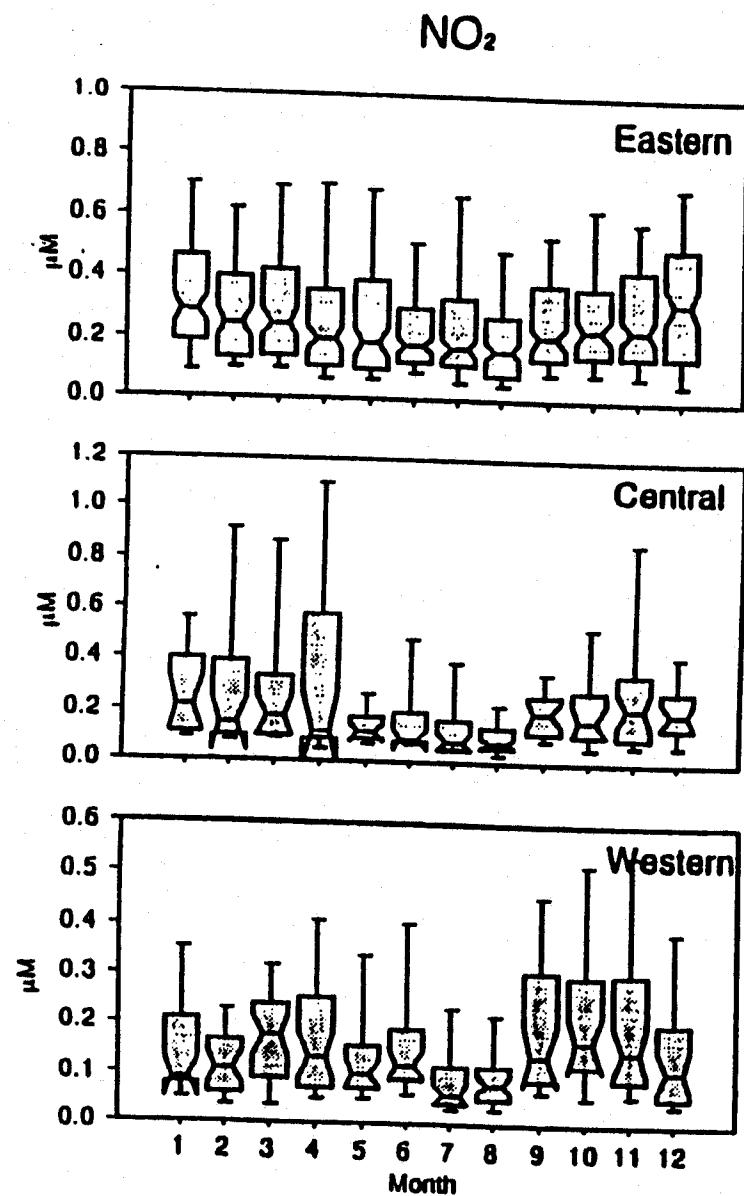


Figure 5

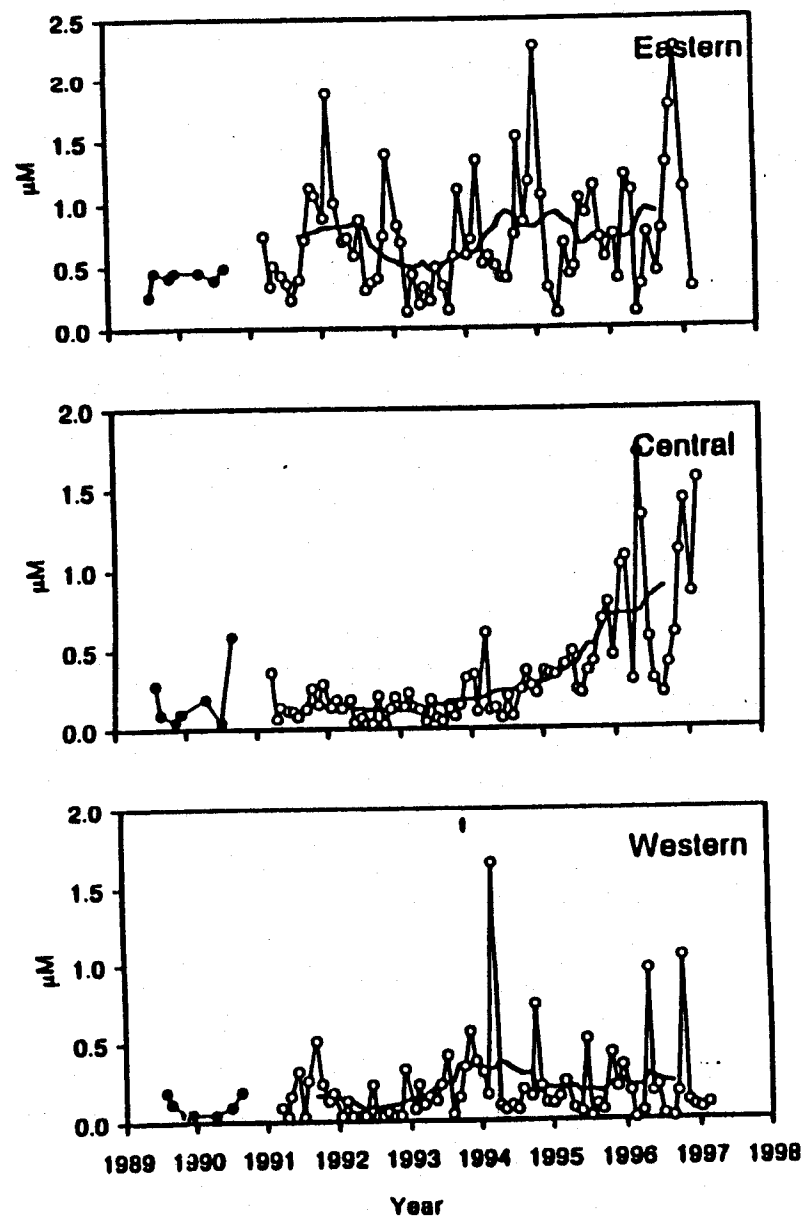
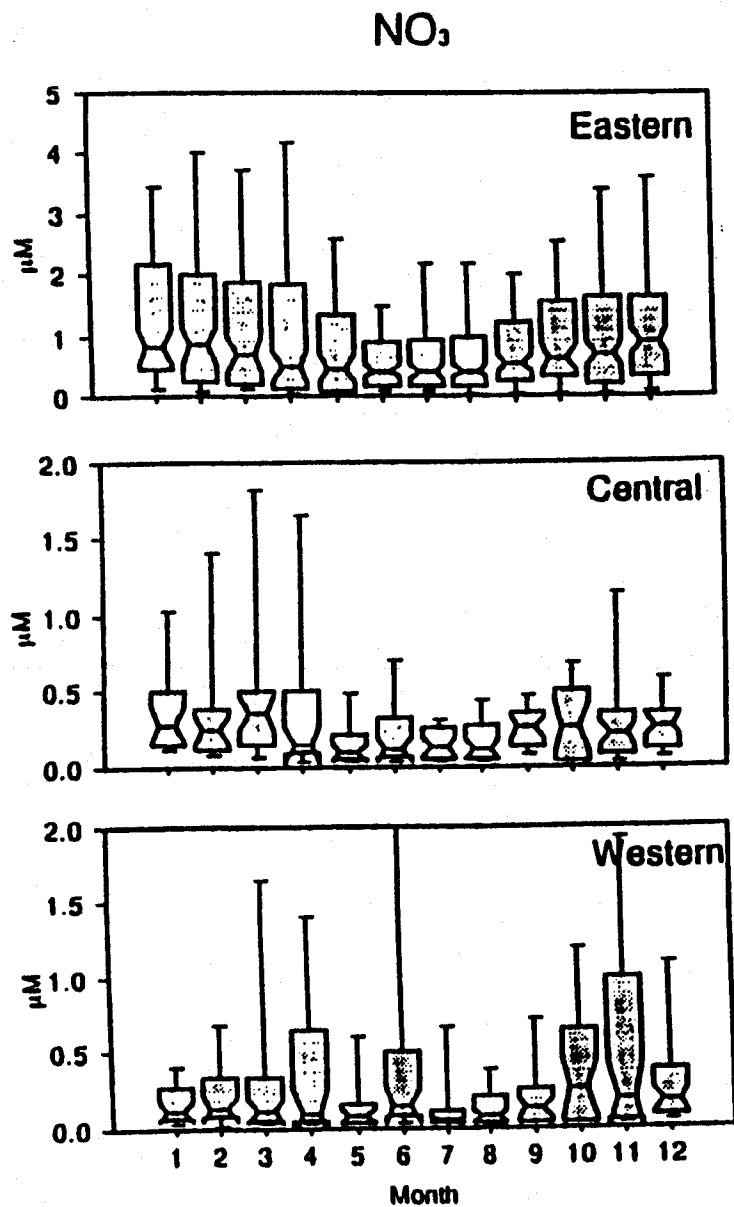


Figure 6

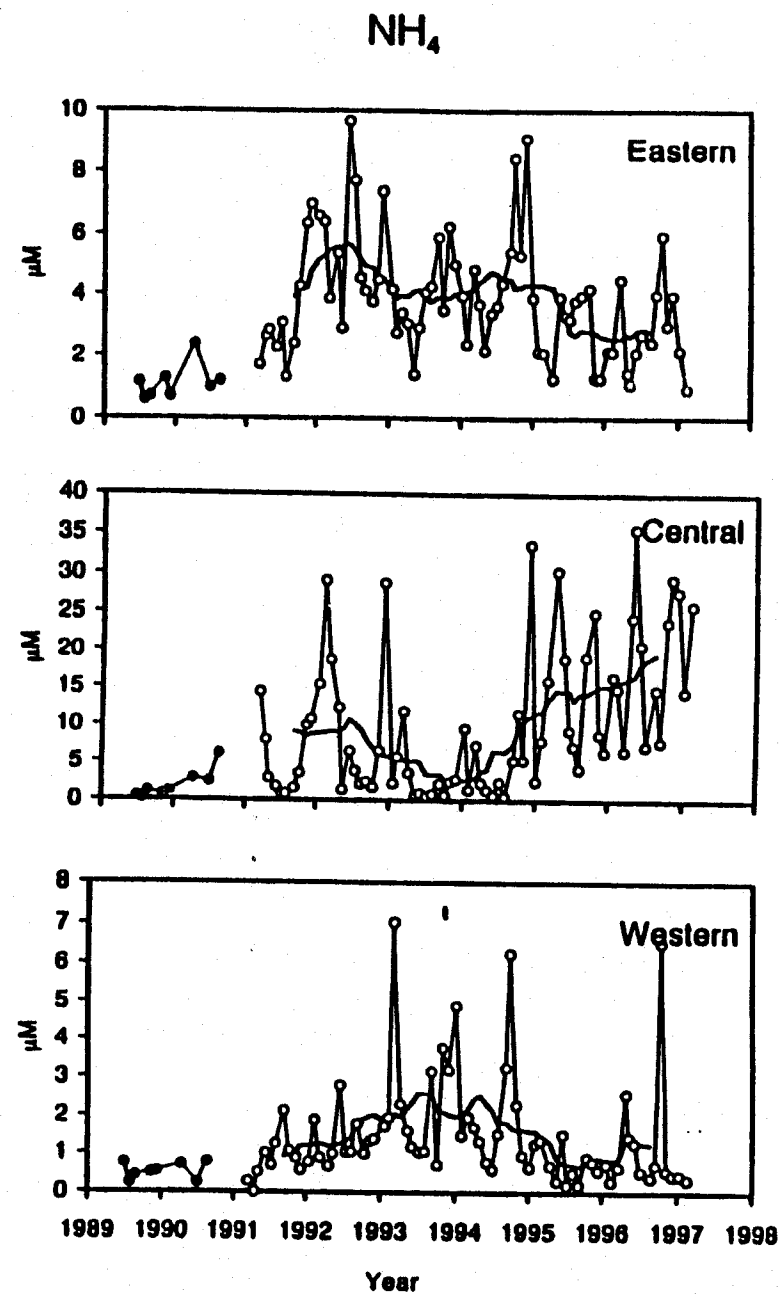
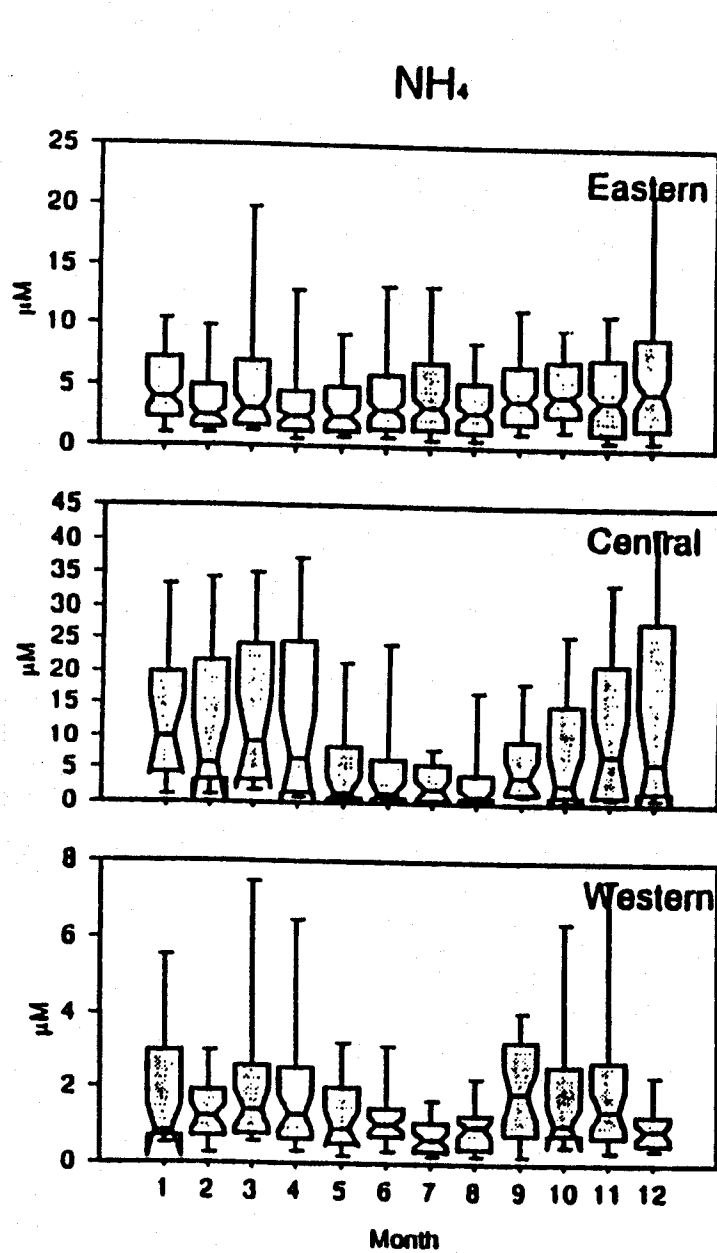


Figure 7

Turbidity

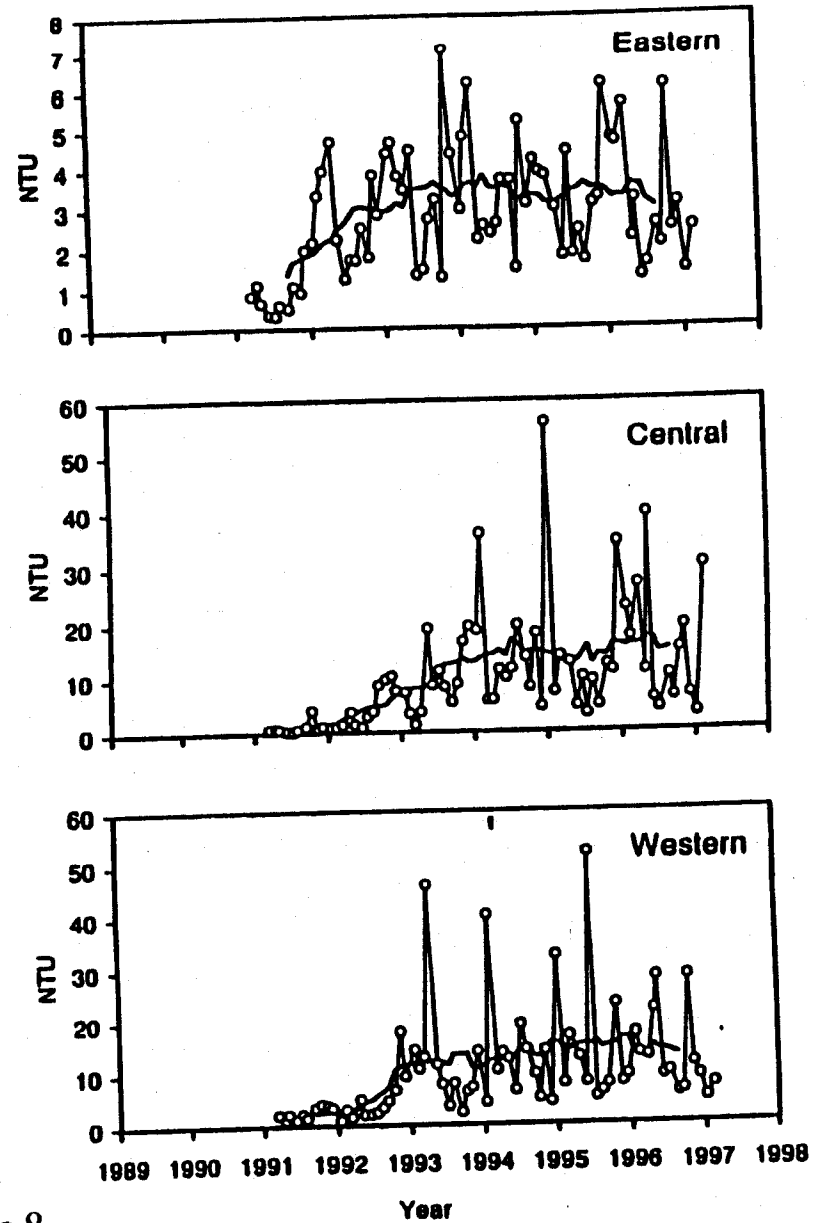
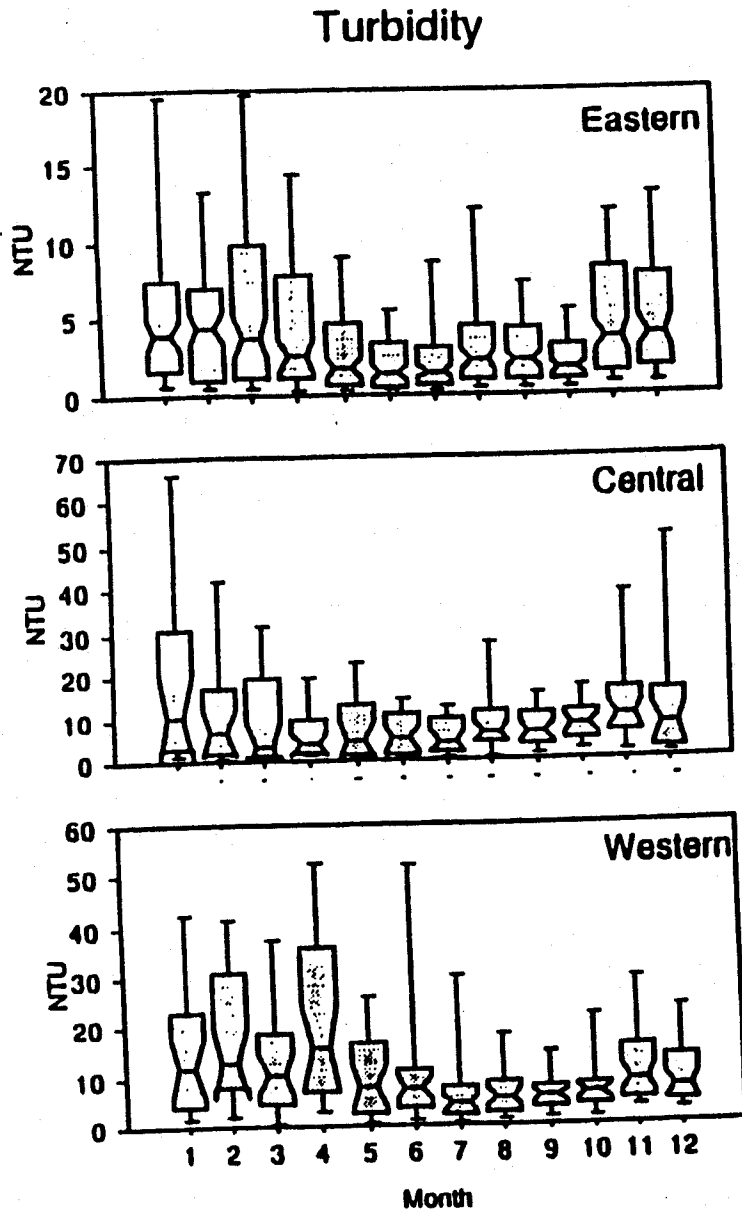


Figure 8

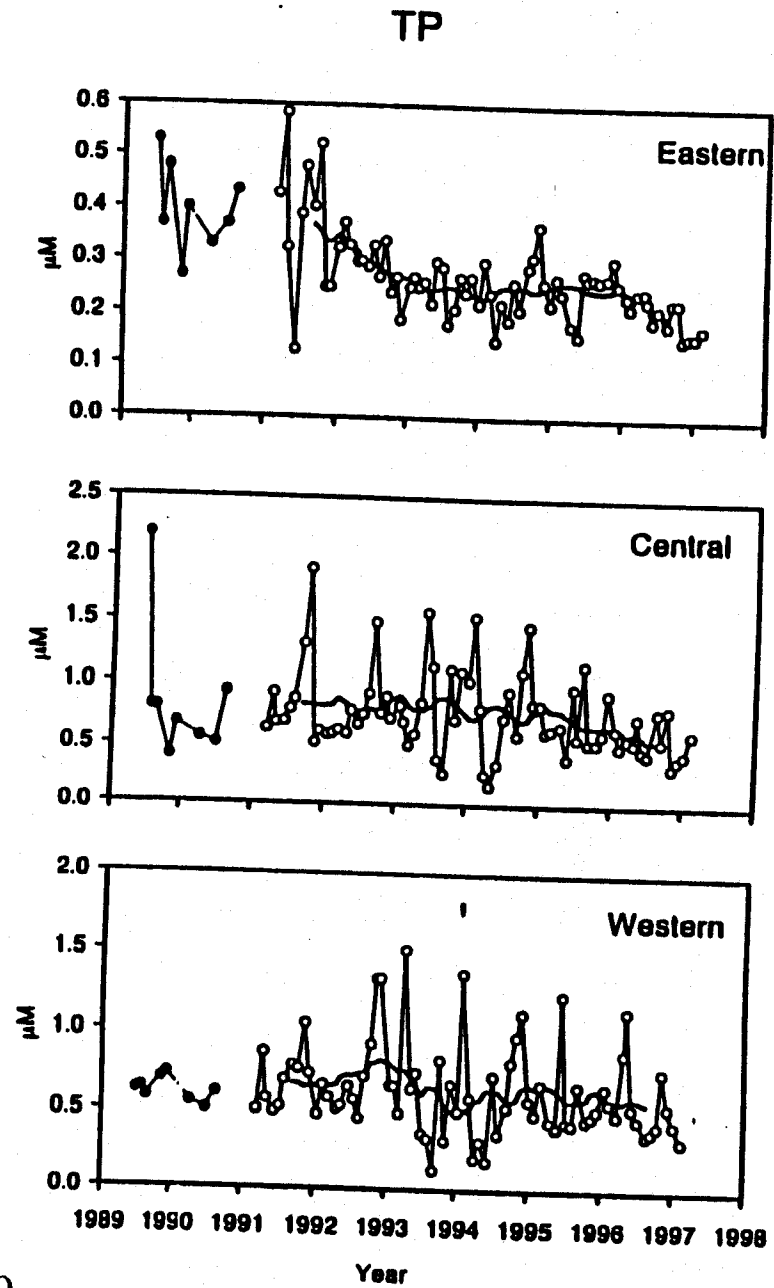
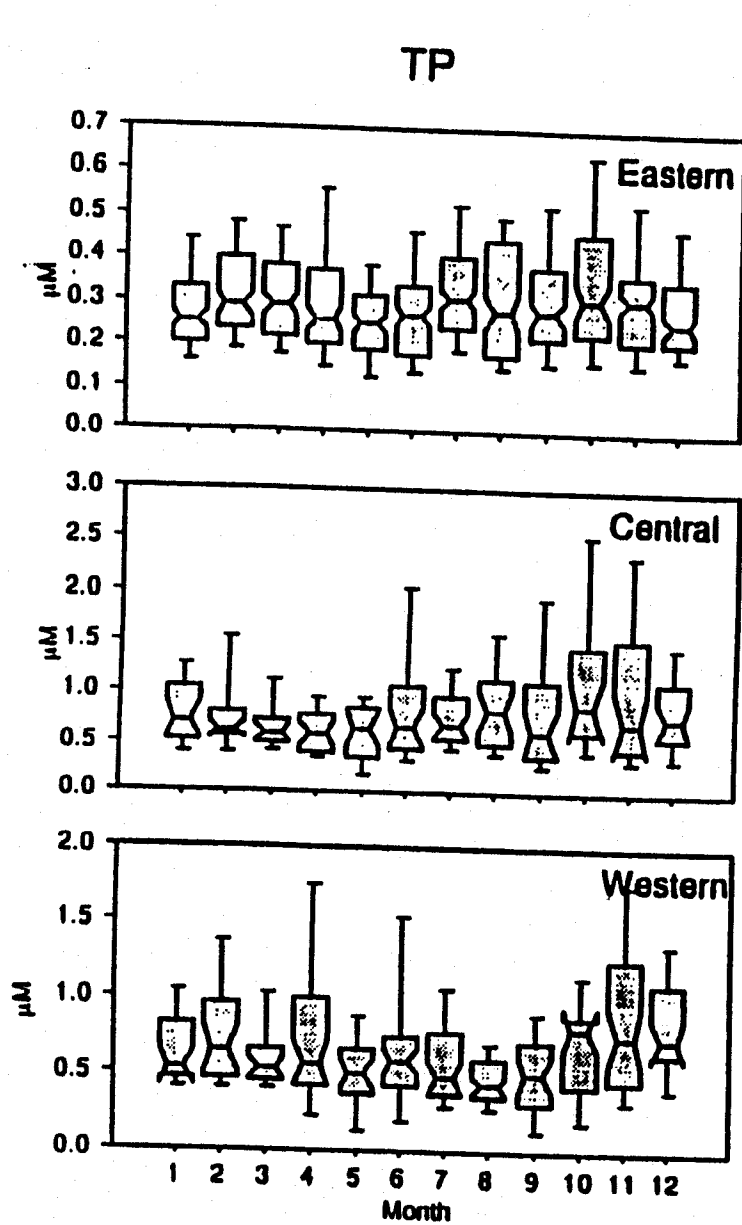


Figure 9

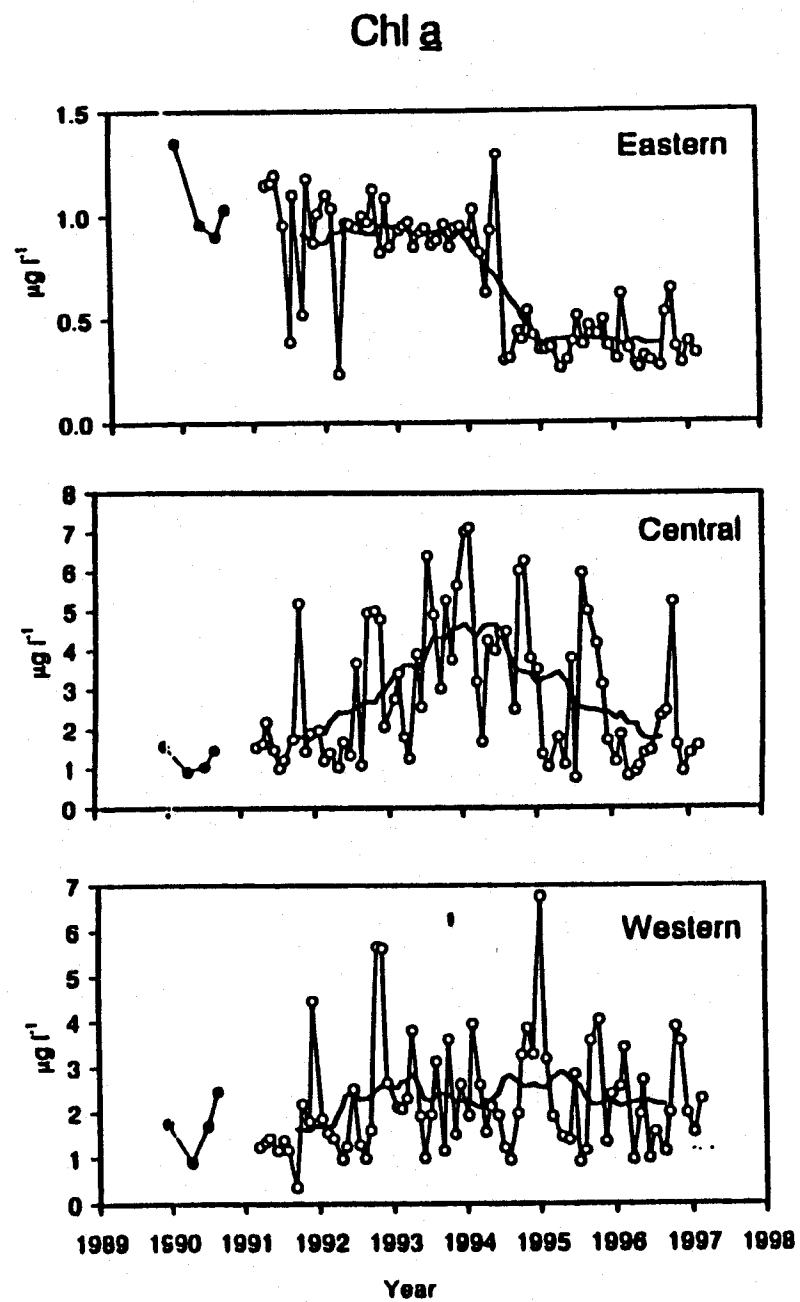
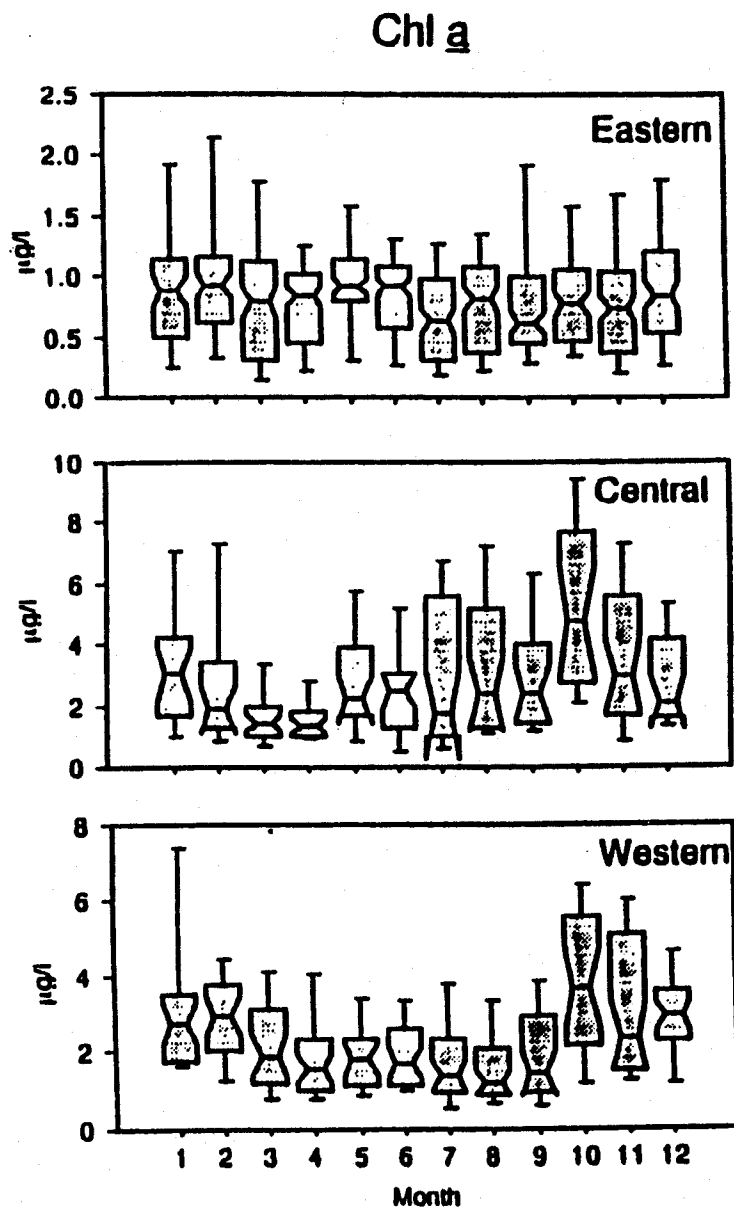


Figure 10

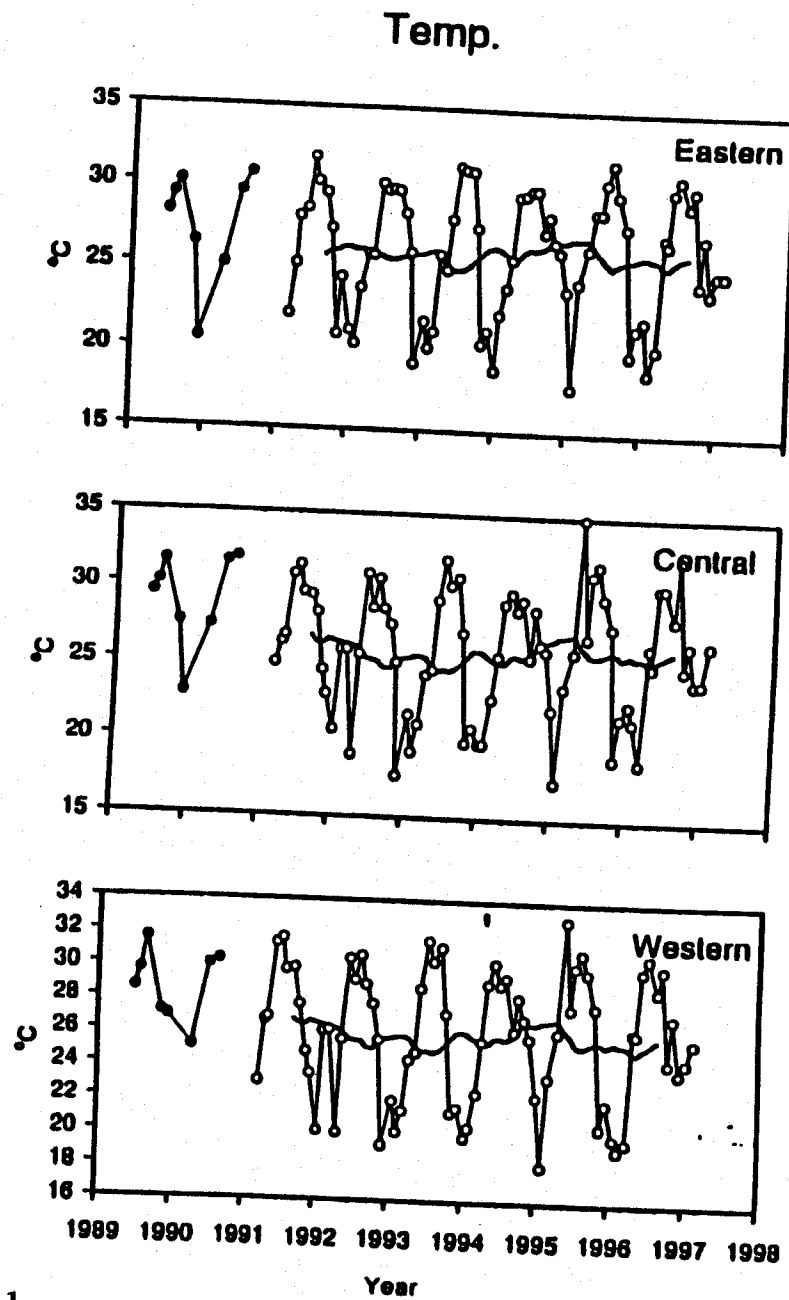
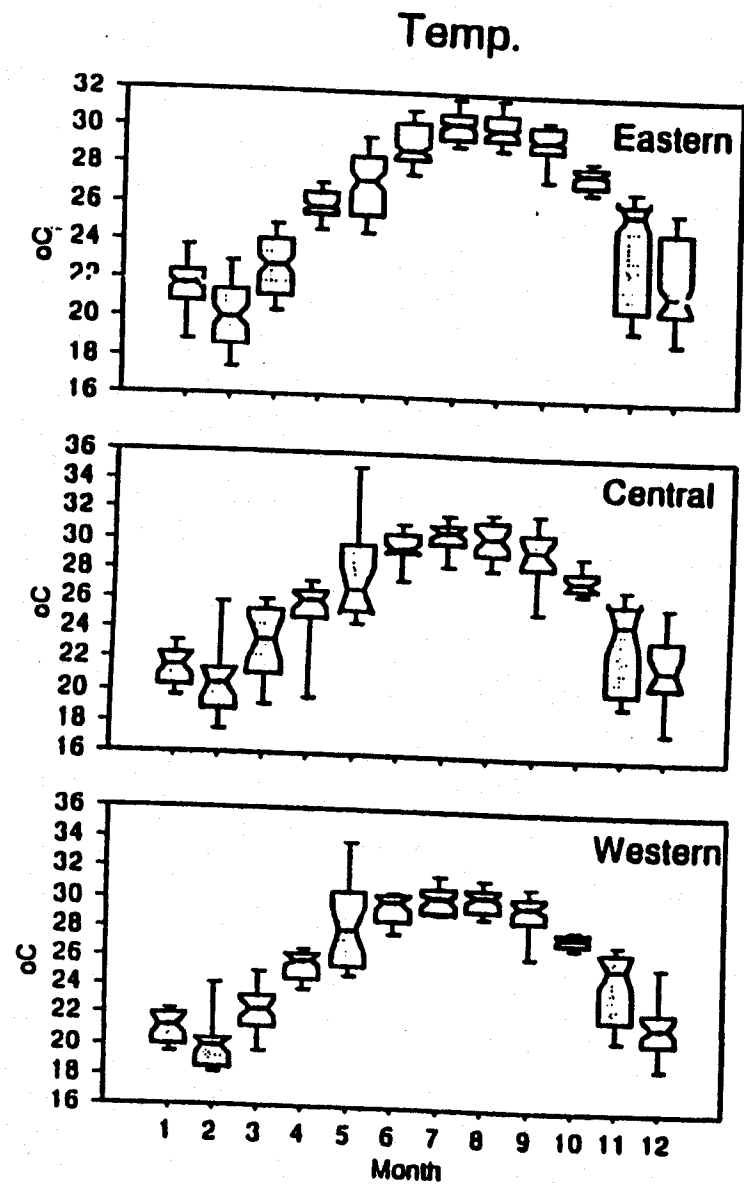


Figure 11

DO_{sat}

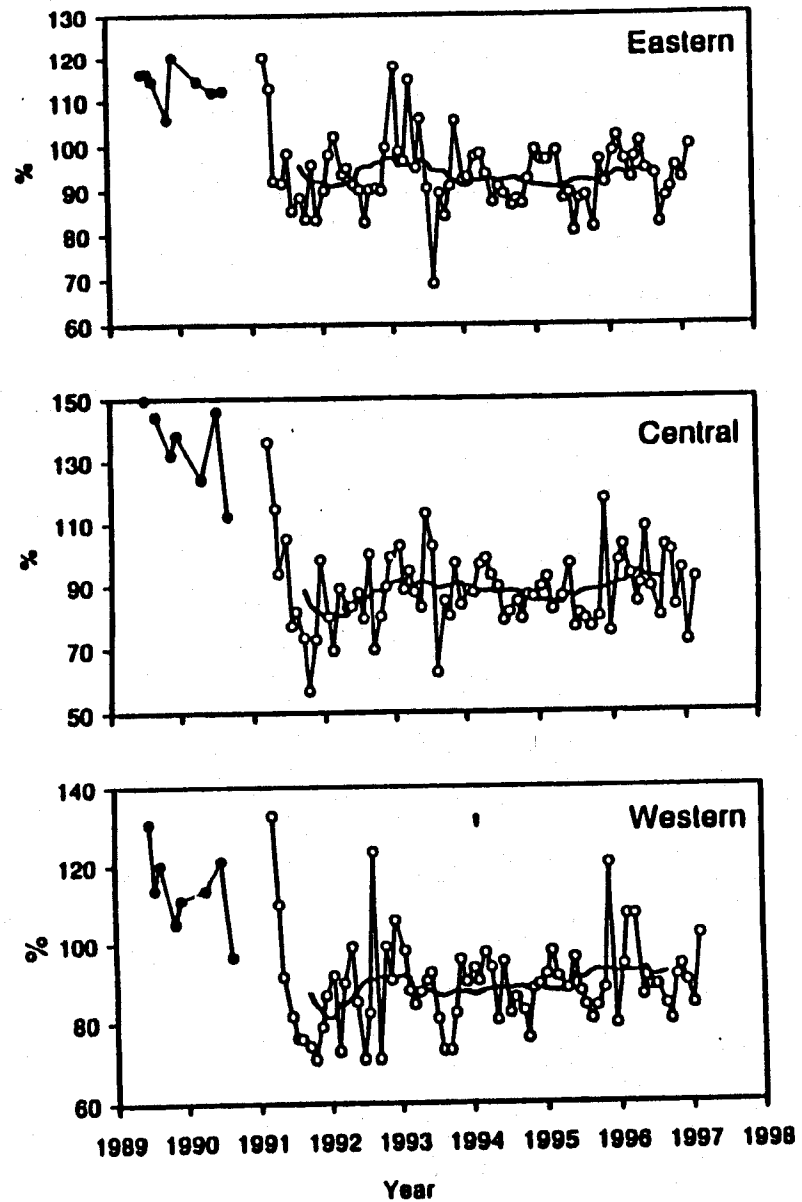
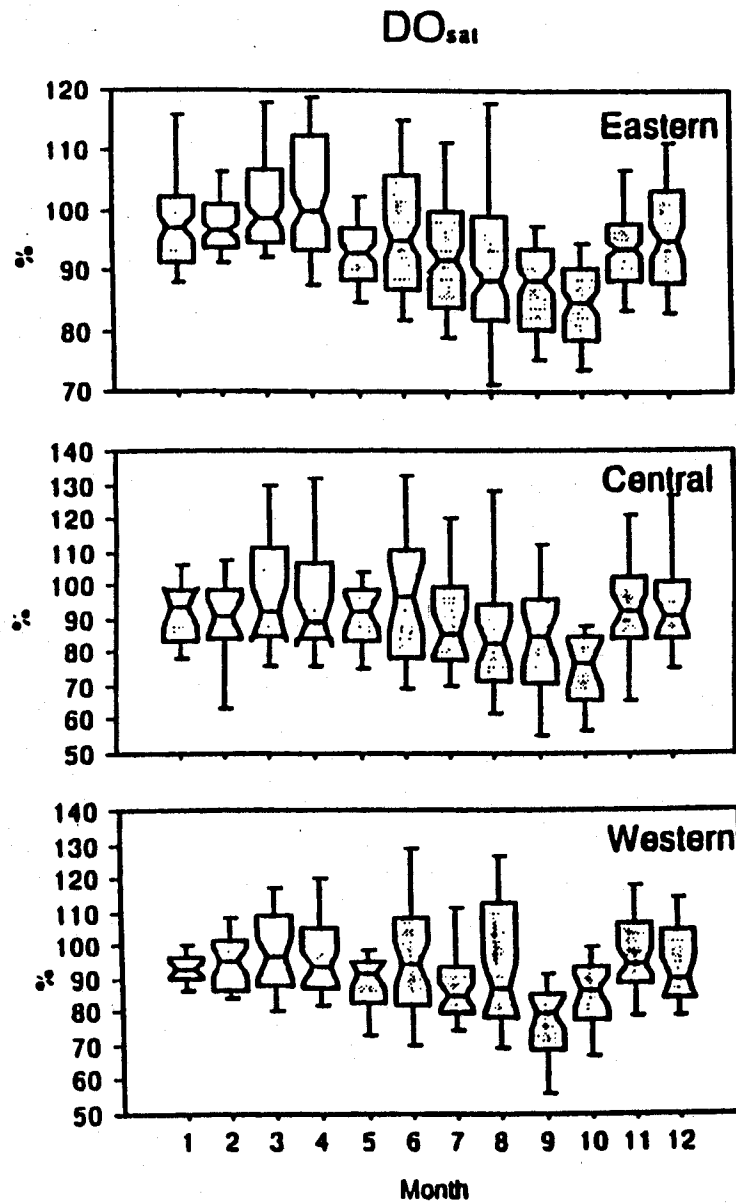


Figure 12

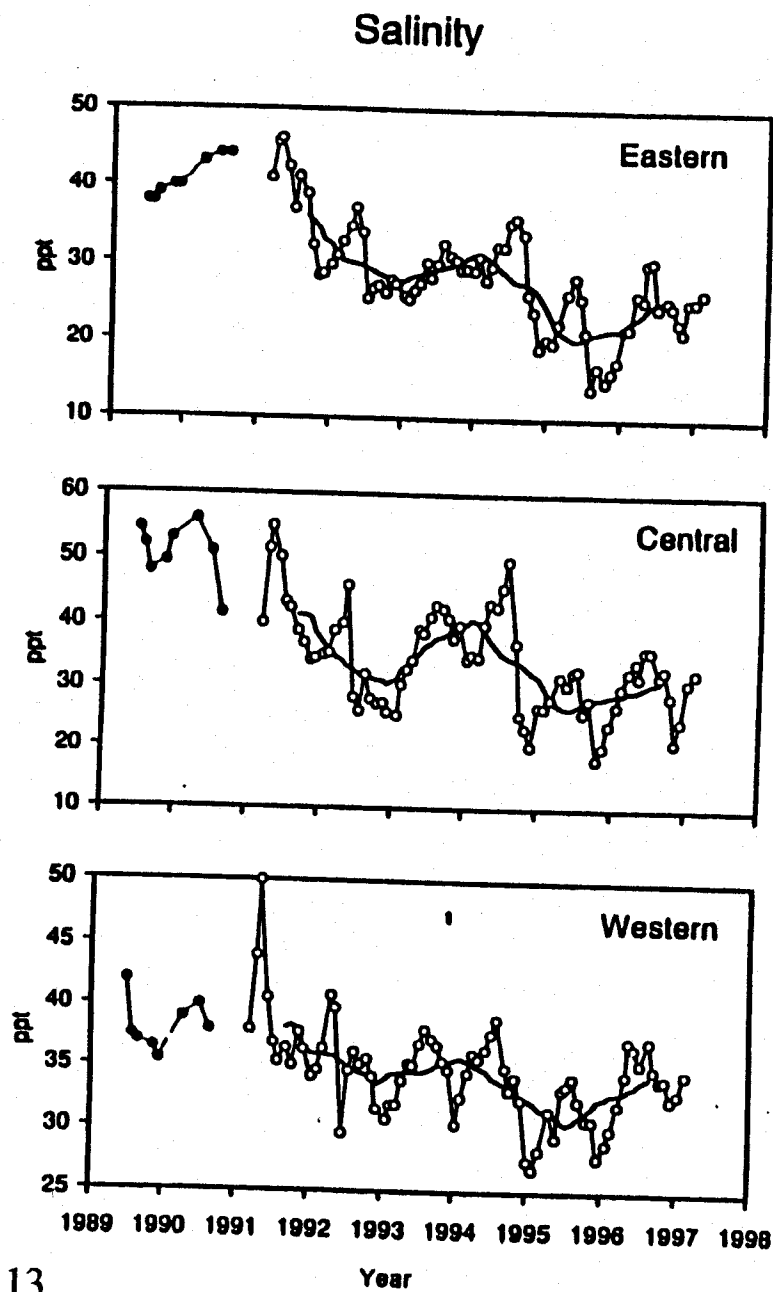
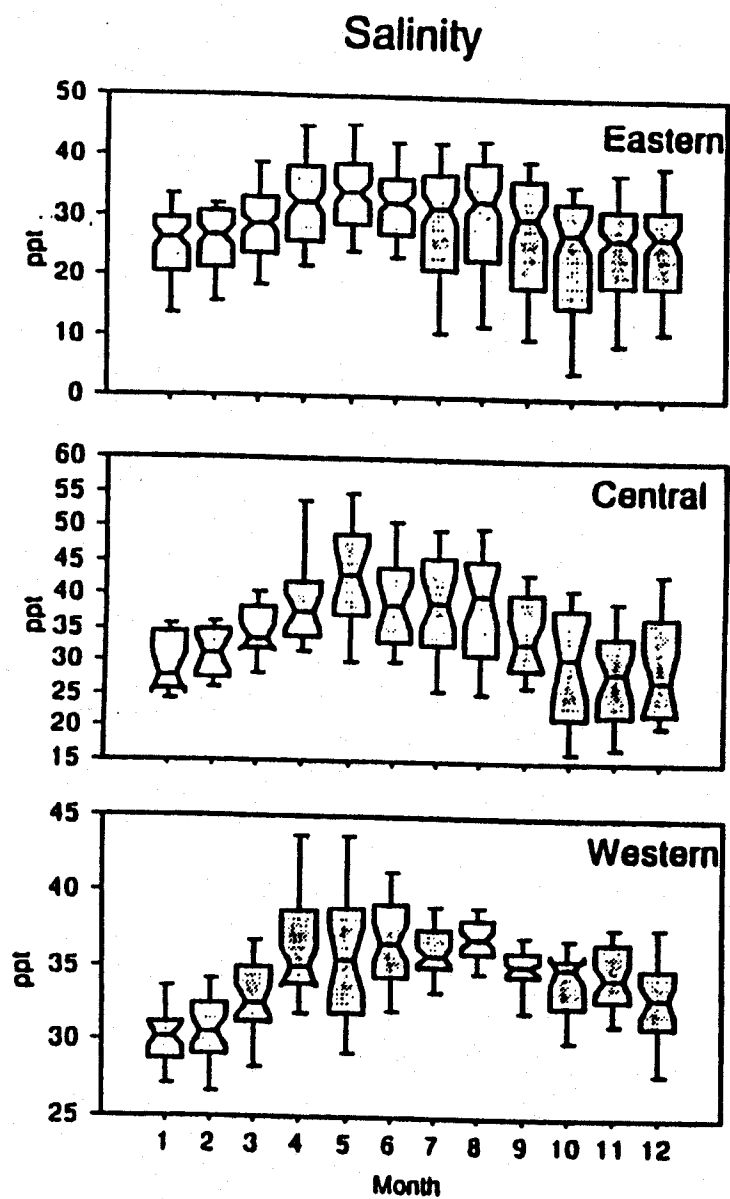


Figure 13

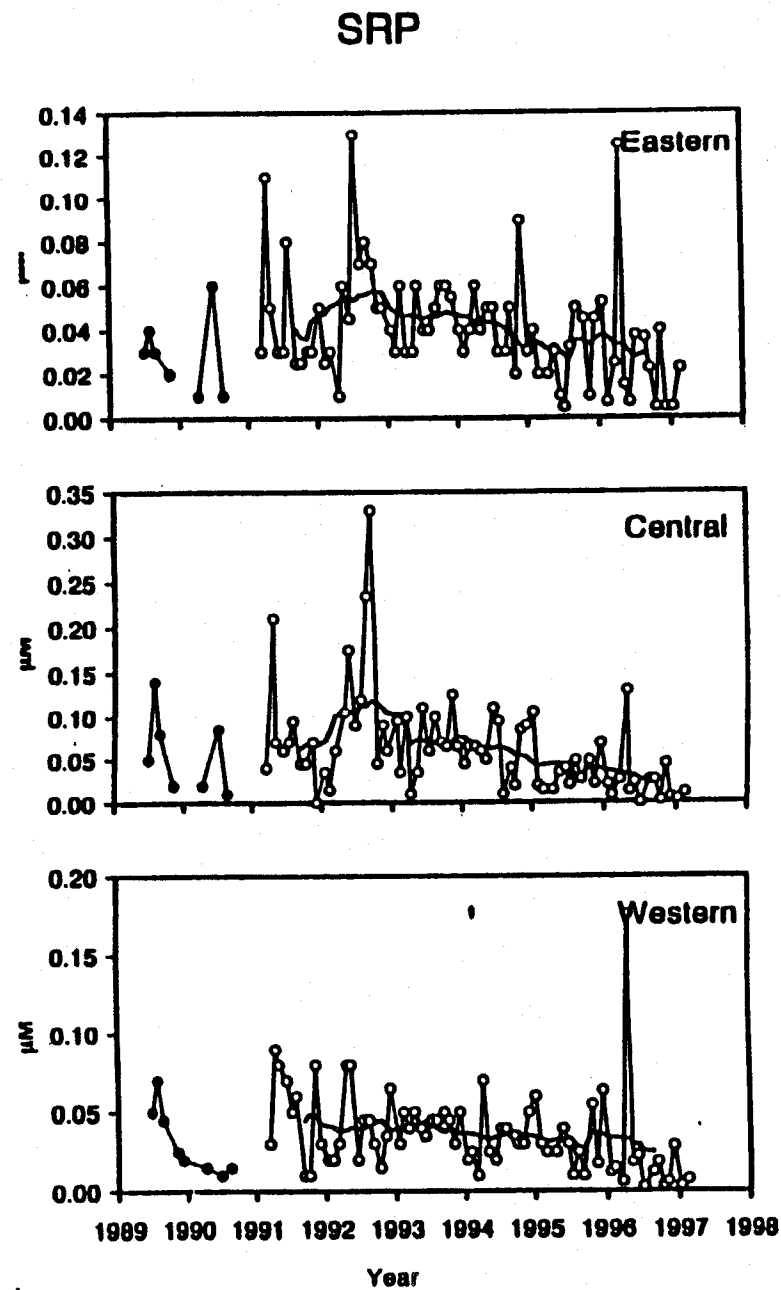
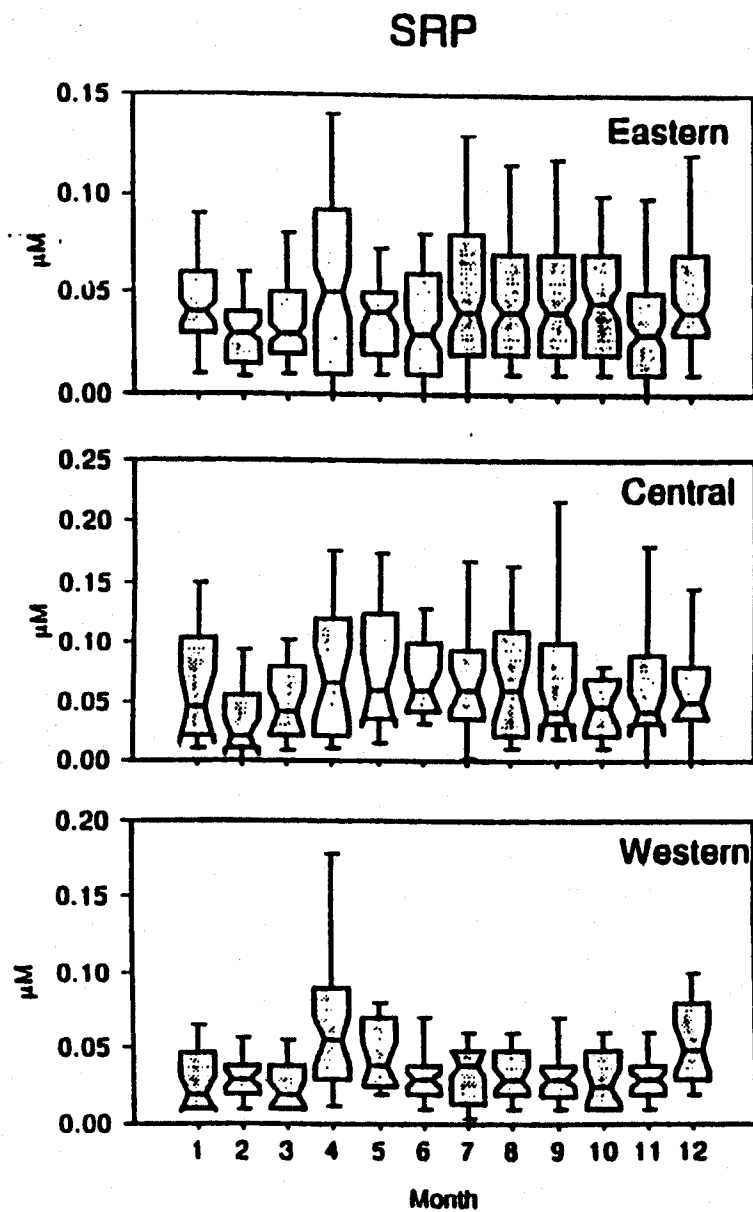


Figure 14

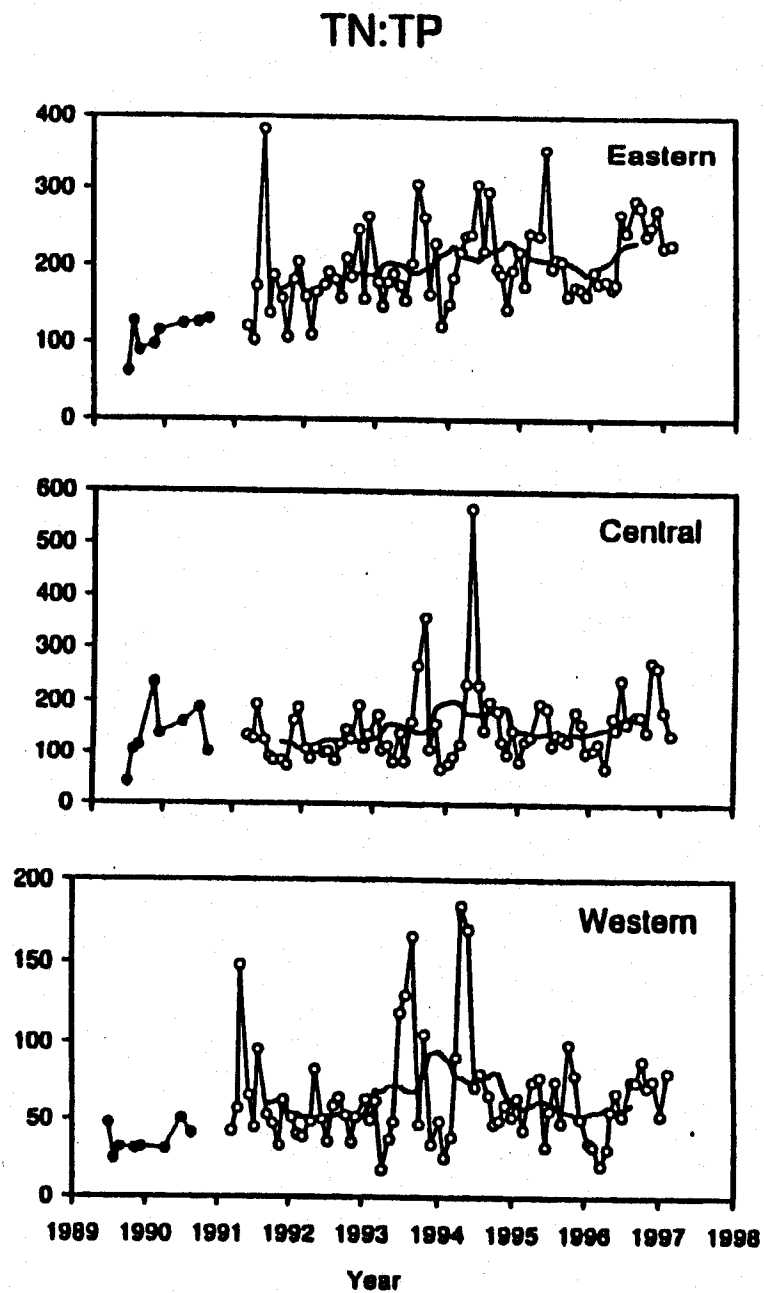
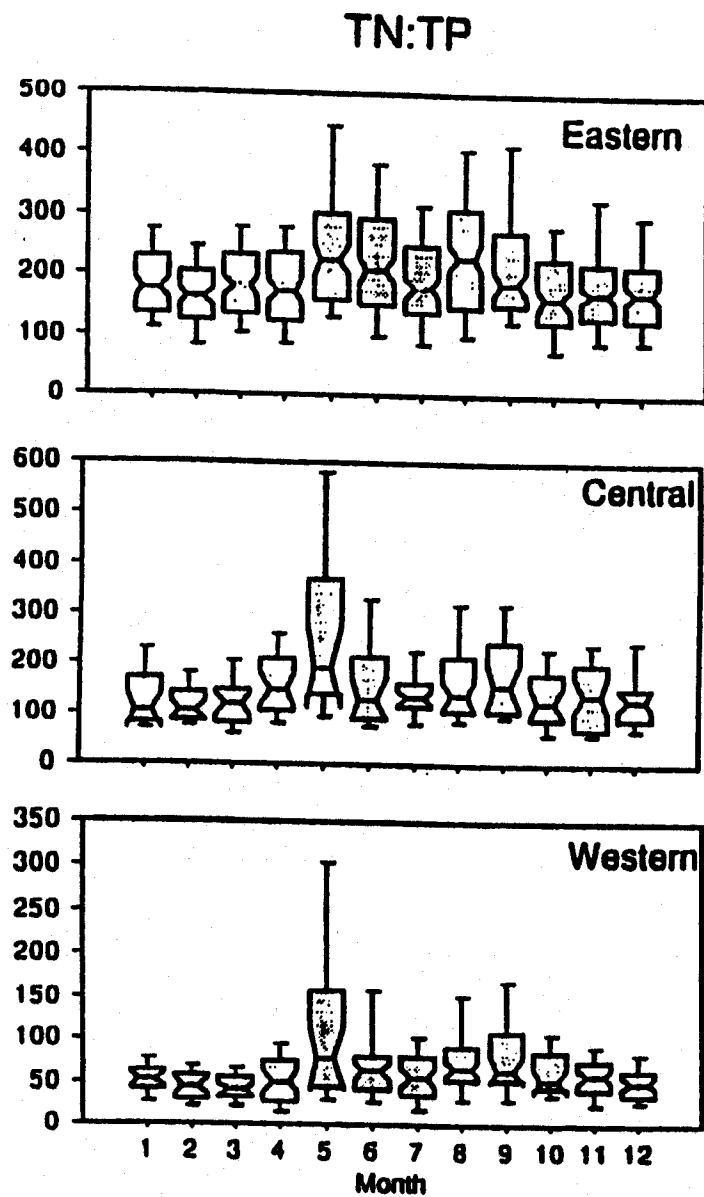


Figure 15

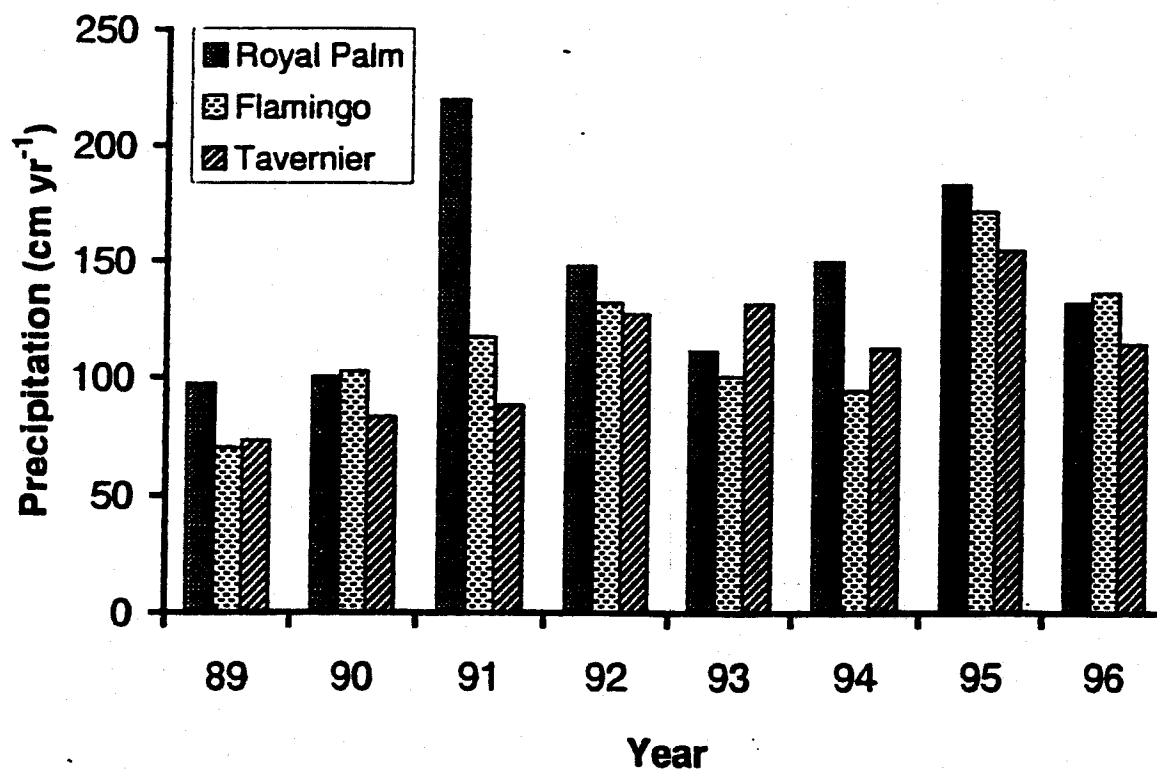
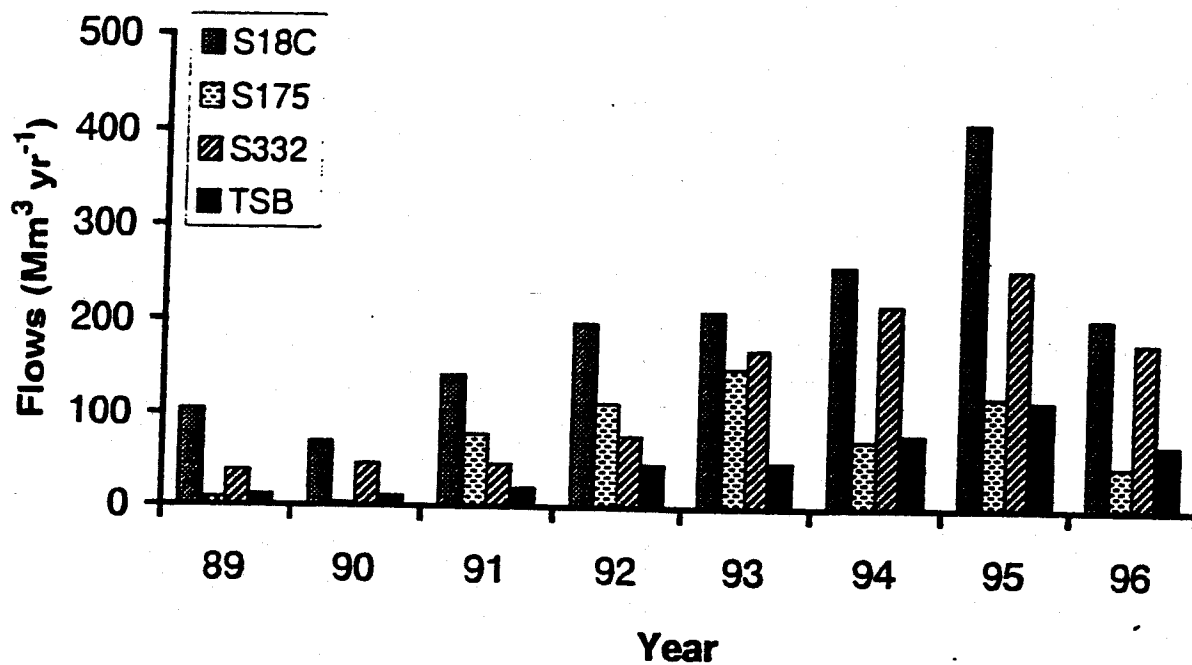
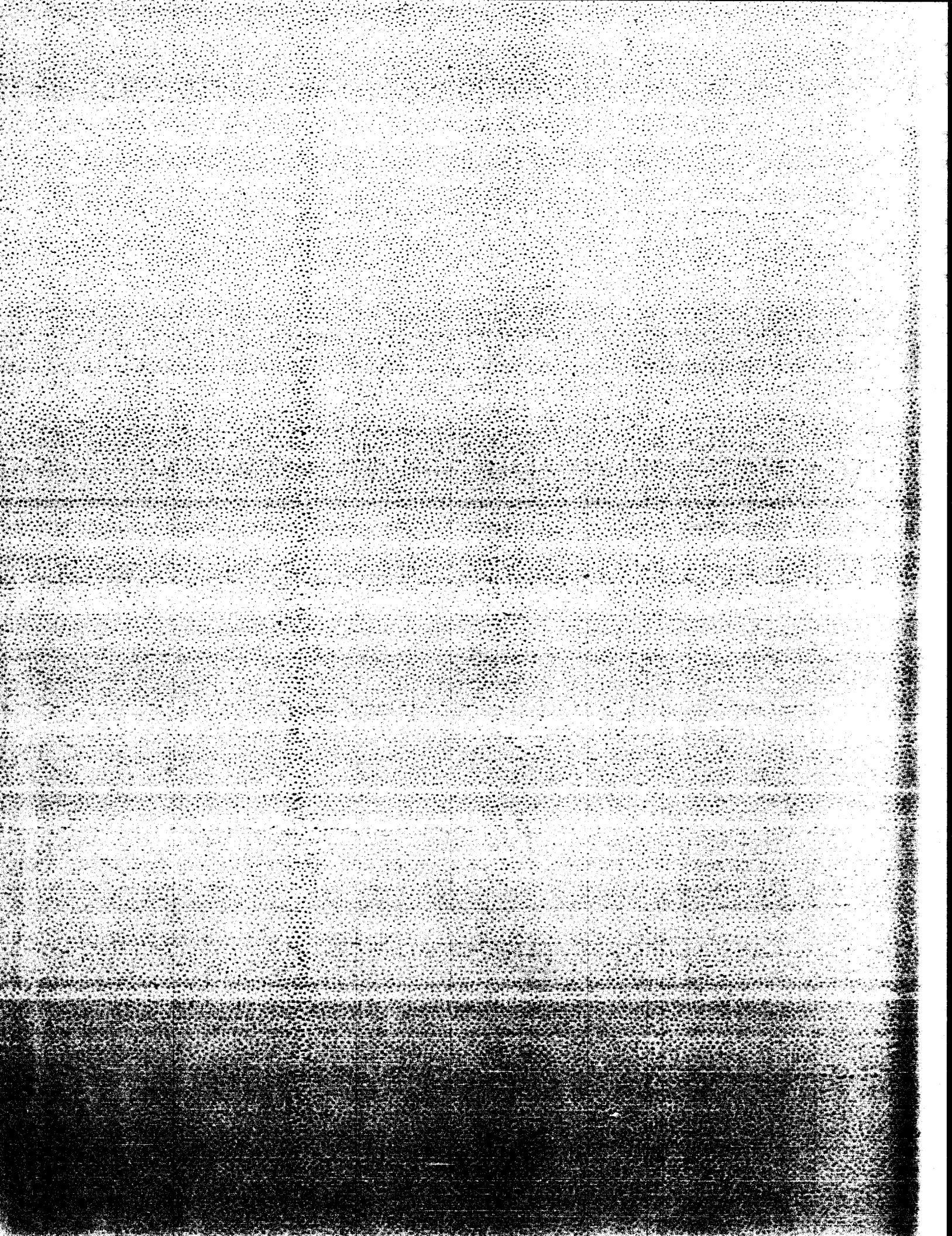


Figure 16

FLORIDA BAY: Nutrient Loading Analysis



**EFFECTS OF FRESHWATER INPUTS AND LOADING OF PHOSPHORUS AND
NITROGEN ON THE WATER QUALITY OF EASTERN FLORIDA BAY**

JOSEPH N. BOYER AND RONALD D. JONES*

**Southeast Environmental Research Program
Florida International University
Miami, FL 33133**

***serp@servax.fiu.edu, 305-348-3095, 305-348-4096 fax**

**Draft of manuscript accepted for publication (in press) K. R. Reddy (ed.),
Phosphorus Biogeochemistry in Sub-Tropical Ecosystems. CRC Press.**

ABSTRACT: Freshwater flows to the Eastern Florida Bay via Taylor Slough (S175 & S332) and the coastal basin (S18C) fluctuated widely during 1984-96 and were not significantly related to precipitation. However, after 1990, a seven-fold increase in freshwater input was observed. At the same time, the contribution of the S332 to the total flow increased from 47-256 Mm³ yr⁻¹ (17-32%). We believe part of this effect was due to a management strategy of increased pumping at the S332 and that these management efforts were effective in increasing water to the Taylor Slough. Average annual salinity in Eastern Florida Bay during 1989-96 declined by 18 ppt and was significantly related to increased flow ($r^2=0.75$) but not to precipitation. TP loading ranged from 0.9-7.7 metric tons yr⁻¹ and was significantly related to flow ($r^2=0.82$) with the average concentration being 0.32 μ M (10 ppb). While TP loading increased, ambient TP concentration in Eastern Florida Bay decreased from 0.4 to 0.2 μ M. TN loading ranged from 98.7-635 metric tons yr⁻¹ and was also highly correlated with flow ($r^2=0.92$). Average input TN concentration was 62 μ M while ambient TN concentration in Eastern Florida Bay averaged 55 μ M. Ambient TN:TP ratios in Eastern Florida Bay were maintained at or near the high input TN:TP ratios (mean=224), implying that both the input ecosystem (Everglades) and the receiving waters are P limited. There was no relationship between either TP or TN loading and Chl *a* in Eastern Florida Bay; instead, there was a significant regression with ambient TP concentration ($r^2=0.75$). This indicates that phytoplankton are responding to internally cycled P and not to external loading.

Introduction

For many years, estuaries and coastal environments have been subjected to close scrutiny by scientists, managers, politicians, and the public for signs of stress and damage. The ecological status of an estuary is directly tied to its geomorphology, hydrologic regime, and watershed characteristics. The shape of an estuary can be modified rapidly by dredge and fill activities and slowly by sea level changes. Estuarine hydrology is most affected by modifications and diversions of freshwater inputs which induces changes in the quantity and timing of freshwater flows. The watershed itself may be subject to large changes in land use patterns which can affect both the hydrologic regime and the water quality of freshwater inputs. All of these modifications have occurred as a direct result of human intervention and have resulted in eutrophication of many estuaries worldwide.

The symptoms of eutrophication have stimulated the formation of monitoring and research programs whose purpose is to characterize existing conditions, detect trends over both space and time, and provide insight for further management activity. In the case of Florida Bay, the impetus of such a program was a combination of events during the mid-1980's which included hypersalinity, a seagrass die-off, sponge mortality events, and sustained phytoplankton blooms. In response, a monitoring network was established in 1989 so that trends in water quality could be addressed.

Florida Bay is a wedge-shaped, shallow lagoonal estuary located off the southern tip of the Florida peninsula bounded by the Everglades to the north and open to the Gulf of Mexico along its western margin. The main line of the Florida Keys, a Pleistocene reef, separates Florida Bay from the Atlantic Ocean. Florida Bay receives freshwater runoff from Taylor Slough and the coastal basin of the Everglades at its NE end. Shallow mud banks divide Florida Bay into

relatively discrete basins which restrict water mixing between basins and attenuate both tidal range and current speed.

A spatial analysis of 6 years of data from the monitoring program resulted in the delineation of 3 general zones (Fig. 1) which have robust similarities in water quality (Boyer et al. in press). Eastern Florida Bay is that zone most like a "conventional" estuary in that it has a semi-longitudinal salinity gradient. The Central Bay is a physically isolated area with low freshwater input and high evaporative potential. Western Bay is the zone most influenced by the Gulf of Mexico. Water quality parameters for these zones were analyzed as time series and overall trends were reported (Boyer et al. submitted). In this paper we attempt to relate annual freshwater flows and nutrient loading to P and N concentrations in surface waters of Eastern Florida Bay. We also provide a comparison of nutrient characteristics of Florida Bay with those from other estuarine systems and gain a new perspective on their similarities and differences in the process.

Methods

A total of 28 sampling sites are distributed throughout Florida Bay; some located near the center of the basins, others more evenly spaced so as to give a broad coverage of the area (Fig. 1). Stations were sampled semi-monthly from July 1989-Dec. 1990 and then monthly from Mar. 1991-96. Two consecutive days were required to complete each sampling event.

Water quality parameters measured included salinity (ppt), temperature ($^{\circ}\text{C}$), dissolved oxygen (DO, mg l^{-1}), nitrate + nitrite (NO_x), nitrite (NO_2), ammonium (NH_4), total organic nitrogen (TON), total phosphorus (TP), soluble reactive phosphorus (SRP), total organic carbon (TOC), chlorophyll *a* (Chl *a*, $\mu\text{g l}^{-1}$), alkaline phosphatase activity ($\mu\text{M hr}^{-1}$), and turbidity (NTU). Analytical details are provided in Boyer et al. (in press); all parameters are reported in μM unless otherwise noted.

Freshwater flow data ($\text{m}^3 \text{d}^{-1}$) from 1984-1996 was provided at gaging stations in Everglades National Park (ENP) operated by the South Florida Water Management District (SFWMD) and US Geological Service. The two main sources of overland flow into Taylor Slough are the S175 and S332 structures while the coastal basin and C111 canal system is supplied by the S18C (Fig. 1). There is also a gage at the Taylor Slough bridge (TSB) just downstream from the S175 and S332, which is a more accurate estimate of flow through Taylor Slough as it integrates the two upstream gages. All flow data was summed to get monthly and annual flow (in $\text{Mm}^3 \text{yr}^{-1} = 10^6 \text{m}^3 \text{yr}^{-1}$). Precipitation (cm d^{-1}) at the Royal Palm monitoring site (ENP) was also obtained and summed to get monthly and annual inputs in cm yr^{-1} . We did not have any estimates of groundwater inputs to Florida Bay.

Annual loading of TP and TN (metric tons yr^{-1}) were calculated at the S18C, S175, and S332 gaging stations by William Walker (pers. comm.) and kindly provided to us. No attempt was made to derive P or N loading from the western boundary of Florida Bay; neither was loading from precipitation nor groundwater included in the calculations. These are serious omissions to the nutrient budget but none of these data existed at the time of writing.

The seasonal Kendall- τ analysis was performed on monthly flow and precipitation data to test for monotonic trend (Hirsch et al. 1991). The seasonal Kendall- τ test is a nonparametric regression analysis which determines: direction of trend (+ or -), goodness of fit (τ), statistical significance of fit (P) not accounting for serial correlation, and trend slope estimate over the period of record (TSE in units yr^{-1}). The seasonal Kendall- τ test requires the dataset to be continuous and complete. It cannot detect reversals in trend direction, such as might be seen in the case of interannual oscillations.

Results and Discussion

FRESHWATER INPUTS

The S18C canal accounted for the largest proportion of overland freshwater flow, ranging from 70-435 $\text{Mm}^3 \text{yr}^{-1}$ (Fig. 2). Losses to groundwater through this structure are unquantified, so the actual amount of water entering Florida Bay from this system is not known. However, due to its proximity to distribution, the ratio of actual freshwater input to S18C gage flows are probably closest to unity than for any of the other structures. There was no significant trend in S18C flow for the 1984-96 period of record (seasonal Kendall- $\tau=0.33$, $P=0.22$), but for the period 1990-96 (post 1989 drought), flow did increase significantly by 38 $\text{Mm}^3 \text{yr}^{-2}$ ($\tau=0.69$, $P=0.02$). Flows through the S175 fluctuated from lows of 8.3 and 3.6 $\text{Mm}^3 \text{yr}^{-1}$ in 1989-91 to a high of 152 $\text{Mm}^3 \text{yr}^{-1}$ in 1993. No trend in flow through the S175 was evident ($\tau=0.09$, $P=0.72$). The S332 flows prior to 1992 were $\sim 40 \text{ Mm}^3 \text{yr}^{-1}$; from 1992 onward the flows increased dramatically up to 256 $\text{Mm}^3 \text{yr}^{-1}$ in 1995 (Fig. 2). In addition there was a change in the S332 flow relative to the S18C. Prior to 1992, the S332 made up 19.7% of the combined flow; from 1992 on, the S332 contributed 33.2% of the total. We believe the increase contribution of S332 flow was due to a change in SFWMD policy instituted to increase the hydroperiod of Taylor Slough by continued pumping. The effect of this management strategy was also seen downstream of the S332 as a concurrent increase in flows at TSB (Fig. 2). Annual TSB flows increased from an average of 20 $\text{Mm}^3 \text{yr}^{-1}$ prior to 1992 to 73 $\text{Mm}^3 \text{yr}^{-1}$ afterward.

Precipitation at the Royal Palm station (ENP) was used as a proxy of rainfall input to the lower Everglades. Annual precipitation during 1984-96 ranged from 97-220 cm yr^{-1} , averaging 136 cm yr^{-1} (Fig. 3). A slight trend in monthly precipitation for the 1984-96 period of record was evident ($\tau=0.25$, $P=0.12$), but no trend for 1990-96 was observed ($\tau=0.05$, $P=0.78$). Regressions of detrended monthly precipitation and combined flows at S18C and TSB were significant ($P<0.01$) but explained $<2\%$ of the variance, supplying very little predictive power for any type of modeling effort.

Because precipitation exhibited no trend, the increased flows at the S332 were most probably due to increased pumping rate. This confirms an important point concerning the relationship between combined S175+S332 and TSB flows. The measured difference between gages indicates that there is a significant attenuation in overland flow over a short distance. The TSB:(S332+S175) flow ratio remained relatively consistent for the period of record, averaging 0.22 which can be explained by the fact that most of the water pumped at the S332 acts to

recharge the local groundwater system rather than become entrained as overland flow. It is clear then that increased pumping at the S332 is directly translated to increased TSB flows but it is in no way understood just how much of this water actually gets to Florida Bay. The consistency of the TSB:S332 flow ratio indicates that there is no disproportionate increase in groundwater loss (or recycling) with increased pumping rates at the S332. Any recycling of Taylor Slough water via groundwater return, due to high hydraulic conductivity of the underlying karst limestone, probably occurs downstream of the TSB gage where Taylor Slough abuts the L-31W canal. As mentioned previously, we have no estimates of groundwater flow to Eastern Florida Bay but can only say that it might be substantial as any increase in hydraulic head above the level of Florida Bay will result in an input to the system.

The median annual salinity in Eastern Florida Bay declined from 40 ppt to 22 ppt during 1989-96 (Boyer et al. submitted). As precipitation during this period did not increase significantly, increased overland and groundwater flows may have accounted for the observed salinity decline. However, we must stress the fact that the volume of direct precipitation to Florida Bay dwarfs the maximum possible freshwater input from land. If we assume Eastern Florida Bay to be 1000 km² and 1 m deep, its volume then is 10⁹ m³. For 1995 the annual precipitation was 184 cm yr⁻¹ or 1.84 x 10⁹ m³; the overland flow estimate (S18C+TSB) was 0.53 x 10⁹ m³ or <30% the volume of precipitation. Therefore, a small error in precipitation measurement can be translated to a large change in salinity. However, since significant landward salinity gradients are routinely observed, it is unlikely that these patterns can be explained by precipitation.

In addition to precipitation, evaporation is also very important in salinity determination. Only one pan evaporation rate measurement at one site in Florida Bay has ever been measured (M. Robblee, personal communication). Assuming that rate (4 mm d⁻¹) to be constant results in a possible loss of 1.46 x 10⁹ m³ yr⁻¹, a value similar to the annual average precipitation input of 1.36 x 10⁹ m³ yr⁻¹. The average annual net water flux (Evaporation - Flow - Precipitation, sensu Smith and Atkinson 1994) of Eastern Florida Bay was out of the system; only for 1989 and 1990, the driest years of the study could the Eastern portion of Florida Bay be considered a negative estuary. On average, freshwater inputs to Eastern Florida Bay exceeded evaporation by 0.26 x 10⁹ m³ yr⁻¹, which is low compared to many other estuaries (Smith and Atkinson 1994). This net flux volume is underestimated by omission of groundwater inputs and by the tendency for pan evaporation rates to be high. Never the less, this flux volume can account for much of the salinity change for the period of record.

We believe that increased freshwater inputs to Taylor Slough and the coastal basin were important in alleviating the hypersalinity in Eastern Florida Bay. Overland flows to Eastern Florida Bay during this time period increased seven-fold ($\tau=0.38$, $P=0.008$), while precipitation did not. The regression of salinity with freshwater input (Fig. 4) was highly significant ($P=0.001$) with flow explaining 75% of the variance. What may be more important is the contribution of groundwater to the equation. We must stop thinking of overland flow as being separate from groundwater flow. Instead we should realize that any increase in hydraulic head is translated as a flow to Florida Bay. Continued pumping at the S332 most probably acts to "saturate the sponge" alleviating the deficit and allowing natural precipitation to become runoff.

NUTRIENT LOADING EFFECTS

Annual TP loading estimates for 1984-96 ranged from 0.9-7.7 metric tons yr^{-1} with the average being 3.8 metric tons yr^{-1} (Fig. 4). Unlike the freshwater inputs, TP loading from the S332 structure did not change with increased pumping, accounting for 24.5% of the total. TP loading was highly correlated with total flow ($r^2=0.82$) indicating a relatively constant TP concentration in the incoming water, the average being $0.32 \mu\text{M}$ (~ 10 ppb). TP loading did not increase significantly over the this period of record ($r^2=0.106$, $P=0.48$), but for the period of increasing flow, 1990-95, it increased by 1.4 metric ton yr^{-1} ($r^2=0.95$). We found that during this same time period, average TP concentrations in Eastern Florida Bay declined from $0.4 \mu\text{M}$ (12 ppb) to $0.2 \mu\text{M}$ (6 ppb) (Boyer et al. submitted). Chl *a* concentrations decreased as well, indicating that phytoplankton uptake did not account for the decline in TP.

Although TP loading increased with flow, the concentration of TP in the incoming water was about equal to the ambient TP concentration in Eastern Florida Bay (Fig. 5). This is not the case for most other estuaries as the freshwater input generally has a much higher TP concentration than the ambient waters (see Chesapeake Bay example in Fig. 5). This is a very interesting result as it emphasizes the dichotomy between TP concentration in the incoming water and TP load. Most of the TP in both input and ambient waters was in the form of organic P as the inorganic, SRP fraction was very low (1.4 ppb loading and 1.2 ppb ambient). It is clear then that the TP loading to Eastern Florida Bay is of very low concentration relative to other estuaries, that the input concentration is similar to the ambient concentrations found in the Bay itself, and that most of the TP is in the organic P pool.

Annual TN loading estimates for 1984-96 ranged from 98.7-635 metric tons yr^{-1} with the average being 365 metric tons yr^{-1} (Fig. 6). The trend in TN loading at the S332 structure did not follow TP in that TN loading increased after 1992 from 19.4% to 33.4% of the total. TN loading was also highly correlated with total flow ($r^2=0.92$) with the average concentration of the incoming water being $62 \mu\text{M}$ (~ 0.9 ppm). TN loading did not increase significantly over the period of record ($r^2=0.01$, $P=0.88$) but during 1990-95 it increased by 104 metric ton yr^{-1} ($r^2=0.94$), leading to a five-fold increase in load. TN concentration of the freshwater inputs varied somewhat over the period of record (48-91 μM , Fig. 7), but was not more variable than input TP concentrations (0.20-0.45 μM). Most of the TN as loading and in ambient water was in the form of organic N (data not shown). This is in contrast with other estuaries such as the Chesapeake Bay (Magnien et al. 1992; Boynton et al. 1995) and the Neuse River estuary (Boyer et al. 1988) for which inorganic sources such as NO_3^- and NH_4^+ comprise a large component of the loading.

While TN loading increased greatly during 1990-1995, average TN concentrations in Eastern Florida Bay remained relatively constant at $55 \mu\text{M}$ (0.8 ppm) with no trend detected (Boyer et al. submitted). For comparison, the other data points in Figure 7 are from a lagoon system on the Eastern Shore, MD (Boynton et al. 1996) which has very little freshwater input or output and therefore maintains ambient concentrations > loading concentrations. Once again this illustrates the importance that the concentration of the incoming water has on the water quality of the ecosystem. Although loading increased greatly with flow, the concentration of TN in the incoming water remained only slightly higher than ambient and therefore had little or no effect on the TN concentrations of Eastern Florida Bay.

The TN:TP molar ratio of loading input ranged from 153-367 (mean = 224) which is very high compared to other estuaries (Fig. 8). The input TN:TP ratio has implications in the potential for selective nutrient limitation of in situ primary production. Ambient TN:TP ratios in Eastern Florida Bay are maintained at or near input TN:TP ratios, implying that both the input ecosystem (Everglades) and the receiving waters are P limited. In contrast, Chesapeake Bay and other estuaries display much lower input and ambient TN:TP ratios, most probably as a result of the low TN:TP of non-point source inputs (Nixon and Pilson 1984; Boynton et al. 1995).

Unlike many estuaries which may fluctuate seasonally between N and P limitation, Florida Bay is a consistently P limited ecosystem (Fourqurean et al. 1993; Boyer et al. submitted). Therefore we did not expect Florida Bay to exhibit the usual relationship between TN loading and phytoplankton biomass, as Chl *a*, that is seen in other estuaries (Boynton et al. 1982) and it did not ($P=0.91$). Nor was there a significant relationship between TP loading and Chl *a* ($P=0.89$) as might be expected from lake data (Vollenweider 1976). Instead, there was a significant regression between Chl *a* and ambient TP concentration Eastern Florida Bay ($r^2=0.75$, Fig. 9) indicating that the phytoplankton are responding to internally cycled P and not external loading.

Recently Boynton et al. (1995) compiled loading rates for some 20 estuaries in an effort to compare trophic status among ecosystems. Figure 10 shows the inclusion of our Eastern Florida Bay loading estimates in relation to these other estuaries. It is clear that Florida Bay has the lowest range of TP loading than any other estuary reported, being 2-3 orders of magnitude lower. It is also one of the lowest in TN loading as well (but see Fig. 8). In addition, loading rates in Florida Bay deviate the most from Redfield ratio, being very high (> 200) compared to other estuaries.

The geomorphology of Florida Bay with its shallow basins and mud banks in conjunction with the almost unbroken boundary of the Florida Keys has a very significant impact on advective P and N loading from both the Gulf of Mexico and the Atlantic Ocean. We will not have any estimates of these loadings until a working hydrodynamic model is completed. Addition of advective P and N loading will probably affect mostly Western Florida Bay as there is little mixing to the east on an annual cycle. However, precipitation inputs should also be significant, especially for N. It has been estimated that for many estuaries, N loading by direct precipitation can account for up to a third of the total N load (Fisher et al. 1988; Hinga et al. 1991; Fu and Winchester 1994). This being the case, we would expect the input TN:TP ratio to be even higher than 200, making Eastern Florida Bay look even more P limited than the other estuaries in Fig. 10. Finally, the groundwater loading component may also be quite significant, but because of difficulty in measurement, remains unknown at this time.

Conclusions

For an estuary to exhibit increased P loading while P concentration declines usually requires an increase in either storage or advection. Chl *a* concentrations decreased in Eastern Florida Bay, indicating that phytoplankton uptake did not account for the decline in P in this zone. An increase in seagrass cover or greater binding to sediments with decreased salinity could possibly account for this decline but has not been quantified. We believe the answer lies in the fact that

the TP concentration of the incoming freshwater is approximately equal to ambient TP concentrations in the Bay. We propose that management activities to increase input of freshwater from Taylor Slough and the coastal basin may have effected a significant decline in both salinity and TP concentrations in Eastern Florida Bay via simple dilution.

All the above results point to the simple conclusion that Florida Bay is not like other estuaries of the eastern USA. Many people continue to believe the dogma that Florida Bay is a eutrophic ecosystem polluted by nutrient runoff from agriculture. Were it not for the Everglades marshes, this might indeed be true. We have shown that the actuality is one in which the loading inputs of the limiting nutrient, P, are at or below the ambient concentrations of the Eastern Bay itself. Therefore, nutrient loading reported in metric tons yr^{-1} is misleading because, in this case, it is the input concentration that makes the most difference. Scientists, managers, and politicians who are preparing restoration plans, developing systems models, and setting funding priorities should be made aware of these facts and the public should be informed as to what really matters to the health of Florida Bay.

ACKNOWLEDGMENTS

We wish to thank the Pete Lorenzo, Jeff Absten, Tom Frankovich, and all the other field and laboratory technicians involved with this project over the years. We especially want to thank Bill Walker for providing the freshwater loading estimates. This study was supported by grants from the South Florida Water Management District (C-7919) and Everglades National Park (CA5280-2-9017). This is contribution #xx of the Southeast Environmental Research Program at Florida International University.

LITERATURE CITED

- BOYER, J. N., D. W. STANLEY, R. R. CHRISTIAN, AND W. M. RIZZO. 1988. Modulation of nitrogen loading impacts within an estuary, p. 165-176. In W. L. Lyke and T. J. Hoban (eds.), Proceedings of the American Water Resources Association, Symposium on Coastal Water Resources. AWRA Technical Publication Series TPS-88-1. AWRA, Bethesda, MD.
- BOYER, J. N., J. W. FOURQUIREAN, AND R. D. JONES. 1997. Spatial characterization of water quality in Florida Bay and Whitewater Bay by multivariate analysis: Zones of similar influence (ZSI). Estuaries 20:743-758.
- BOYER, J. N., J. W. FOURQUIREAN, AND R. D. JONES. (submitted). Seasonal and long term trends in the water quality of Florida Bay (1989 - 1997). Estuaries.
- BOYNTON, W. R., W. M. KEMP, AND C. W. KEEFE. 1982. A comparative analysis of nutrients and other factors influencing estuarine phytoplankton production, p. 69-90. In V. S. Kennedy (ed.), Estuarine Comparisons. Academic Press, New York.
- BOYNTON, W. R., J. H. GARBER, R. SUMMERS, AND W. M. KEMP. 1995. Inputs, transformations, and transport of nitrogen and phosphorus in Chesapeake Bay and selected tributaries. Estuaries 18:285-314.
- BOYNTON, W. R., J. D. HAGY, L. MURRAY, C. STOKES, AND W. M. KEMP. 1996. A comparative analysis of eutrophication patterns in a temperate coastal lagoon. Estuaries 19:408-421.

- FISHER, D. J., J. CERASCO, T. MATTHEW, AND M. OPPENHEIMER. 1988. Polluted coastal waters: the role of acid rain. Environmental Defense Fund.
- FOURQUREAN, J. W., R. D. JONES, AND J. C. ZIEMAN. 1993. Processes influencing water column nutrient characteristics and phosphorus limitation of phytoplankton biomass in Florida Bay, FL, USA: Inferences from spatial distributions. Estuarine, Coastal Shelf Science 36:295-314.
- FU, J.-M. AND J. W. WINCHESTER. 1994. Sources of nitrogen in three watersheds of northern Florida, USA: mainly atmospheric deposition. Geochimica et Cosmochimica Acta 58:1581-1590.
- HINGA, K. R., A. A. KELLER, AND C. A. OVIATT. 1991. Atmospheric deposition and nitrogen inputs to coastal waters. Ambio 20:256-260.
- HIRSCH, R. M., R. B. ALEXANDER, AND R. A. SMITH. 1991. Selection of methods for the detection and estimation of trends in water quality. Water Resources Research 27: 803-813.
- MAGNIEN, R. E., R. M. SUMMERS, AND K. G. SELLNER. 1992. External nutrient sources, internal nutrient pools, and phytoplankton production in Chesapeake Bay. Estuaries 15:497-516.
- NIXON, S. W. AND M. E. Q. PILSON. 1984. Estuarine total system metabolism and organic exchange calculated from nutrient ratios: an example from Narragansett Bay, p. 261-290. In V. S. Kennedy (ed.), The Estuary as a Filter. Academic Press, New York.
- SMITH, S. V., AND M. J. ATKINSON. 1994. Mass balance of nutrient fluxes in coastal lagoons, p. 133-155. In B. Kjerfve (ed.), Coastal Lagoon Processes. Elsevier.
- VOLLENWEIDER, R. A. 1976. Advances in defining critical loading levels for phosphorus in lake eutrophication. Memorie dell' Istituto Italiano di Idrobiologia Dott Marco de Marchi 33:53-83.

FIGURE LEGENDS

Fig. 1. Map of Florida Bay zones of similar influence as a result of cluster analysis on mean and SD of five principal component scores. Stations as labeled are: Eastern Bay (+), Central Bay (■), and Western Bay (●). Gaging stations of the water distribution network include the Taylor Slough (S175 and S332), Taylor Slough bridge (TSB), and coastal basin (S18C). RP denotes Royal Palm precipitation gage location.

Fig. 2. Annual potential freshwater inputs to Eastern Florida Bay ($\text{Mm}^3 \text{yr}^{-1}$) via the Taylor Slough (S175, S332, TSB) and coastal basin (S18C).

Fig. 3. Linear regression of annual median salinity (ppt) in Eastern Florida Bay with annual potential freshwater input ($\text{Mm}^3 \text{yr}^{-1}$) from S175, S332, and S18C.

Fig. 4. Annual TP loading in metric tons yr^{-1} for the Taylor Slough (S175 and S332) and coastal basin (S18C).

Fig. 5. Plot of annual average TP concentration in Eastern Florida Bay (μM) against annual average TP concentration of loading. The Florida Bay concentrations (◆) are very low for both input and ambient and fall at or near the 1:1 ratio line while the Chesapeake Bay (¹Magnien et al. 1992; ²Boynton et al. 1995) has much greater TP concentration in the input than is found in the bay (arrows denote the range).

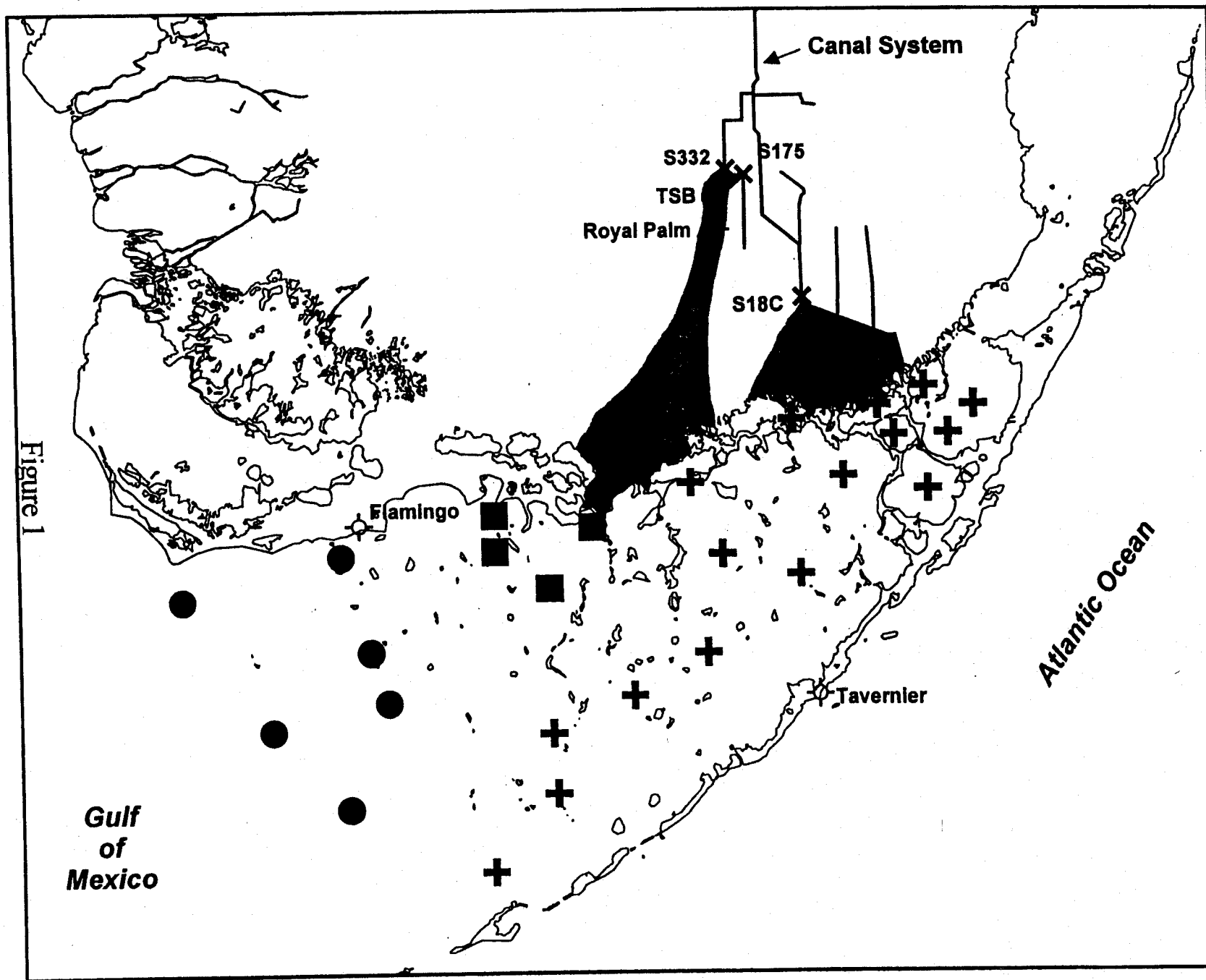
Fig. 6. Annual TN loading in metric tons yr^{-1} for the Taylor Slough (S175 and S332) and coastal basin (S18C).

Fig. 7. Plot of annual average TN concentration in Eastern Florida Bay (μM) against annual average TN concentration of loading. The Florida Bay concentrations (◆) are low for both input and ambient and fall at or near the 1:1 ratio line. Both the Chesapeake Bay (¹Magnien et al. 1992; ²Boynton et al. 1995) and Neuse River estuary (³Boyer et al. 1988) have much higher input TN concentrations than ambient. The Eastern Shore, MD data (⁴Boynton et al. 1996) are representative of a lagoonal system with very little freshwater input and loading (arrows denote the range).

Fig. 8. Plot of annual average TN:TP ratio of loading input and ambient water showing the potential for Eastern Florida Bay to be highly P limited. Both input and ambient TN:TP (◆) fall at or near the 1:1 ratio line with input TN:TP being most variable. TN:TP of Chesapeake Bay (¹Magnien et al. 1992; ²Boynton et al. 1995) are much closer to the Redfield ratio (16:1) with ambient TN:TP being generally higher than input TN:TP (arrows denote the range).

Fig. 9. Regression of median monthly phytoplankton biomass as Chl *a* ($\mu\text{g l}^{-1}$) against concentration of TP (μM) in Eastern Florida Bay.

Fig. 10. Areal annual loads of TN and TP ($\text{mmol m}^{-2} \text{yr}^{-1}$) assuming Eastern Florida Bay to cover 1000 km^2 . TP loads ($\blacklozenge$) are 2-4 orders of magnitude lower than those for 20 other estuaries ($\circ$) while TN loads are only 1-2 orders of magnitude less (¹Boynton et al. 1995). The 16:1 line accentuates the deviation of Eastern Florida Bay from standard Redfield ratio.



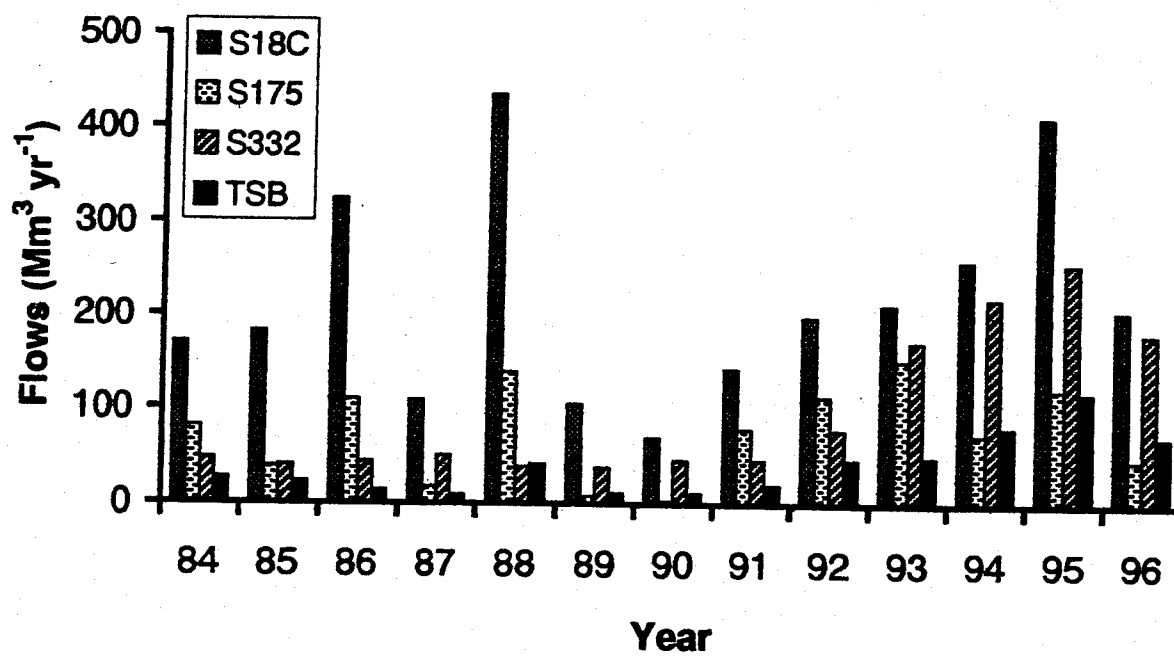


Figure 2

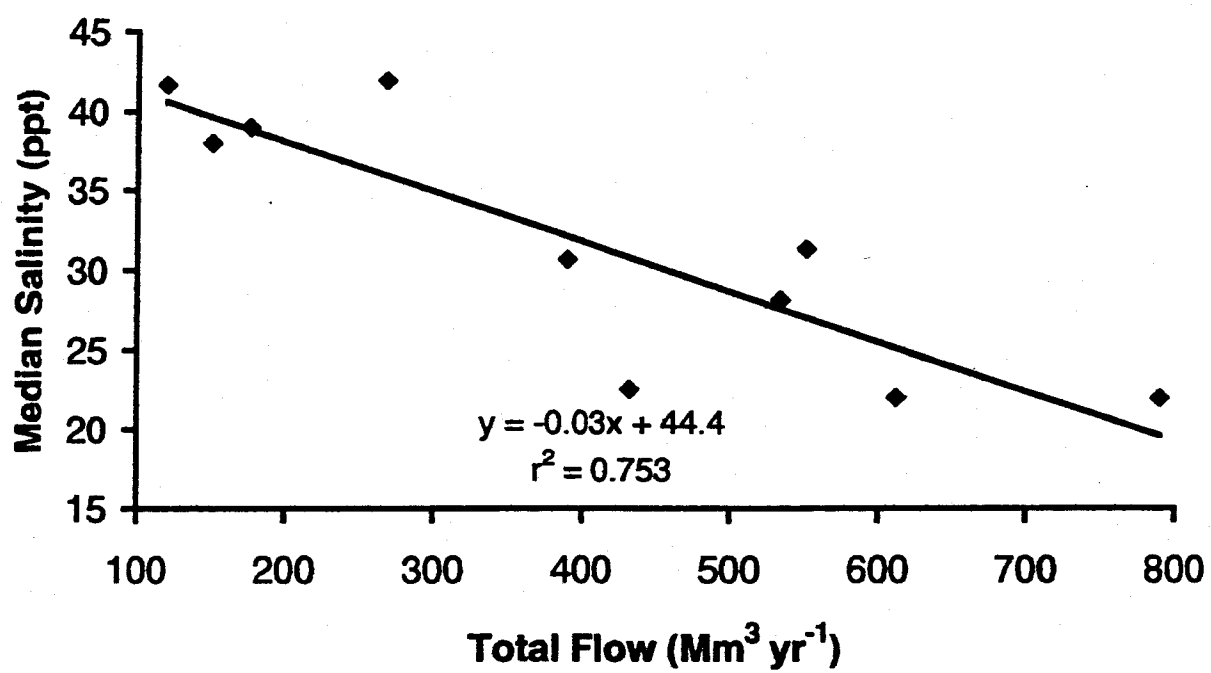


Figure 3

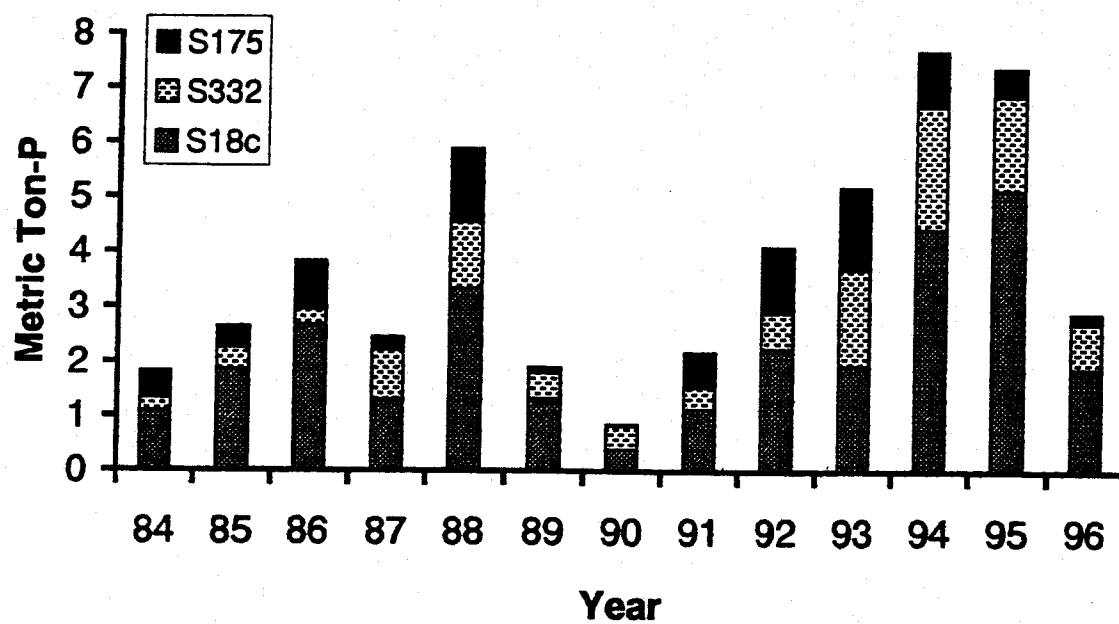


Figure 4

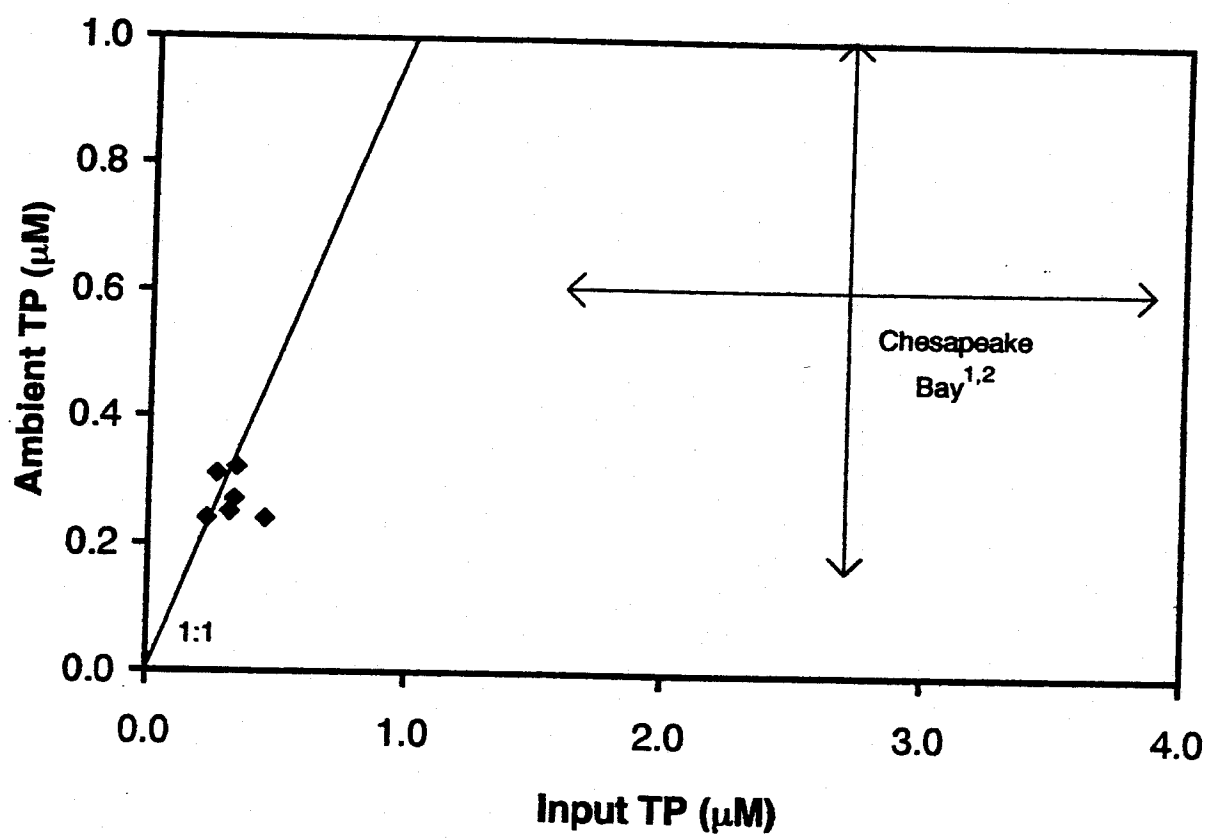


Figure 5

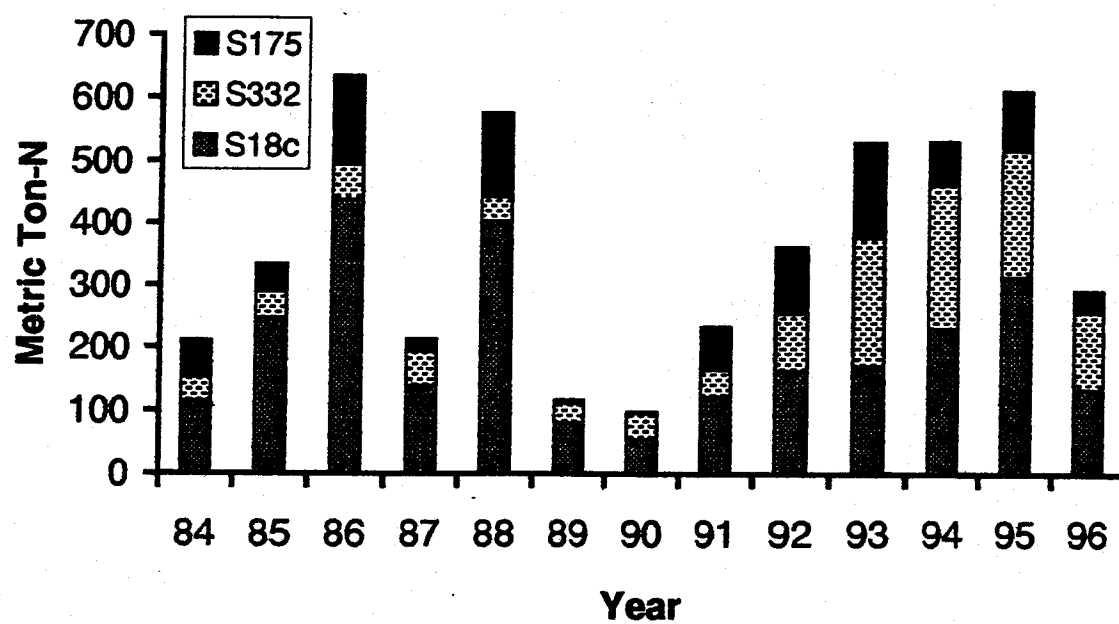


Figure 6

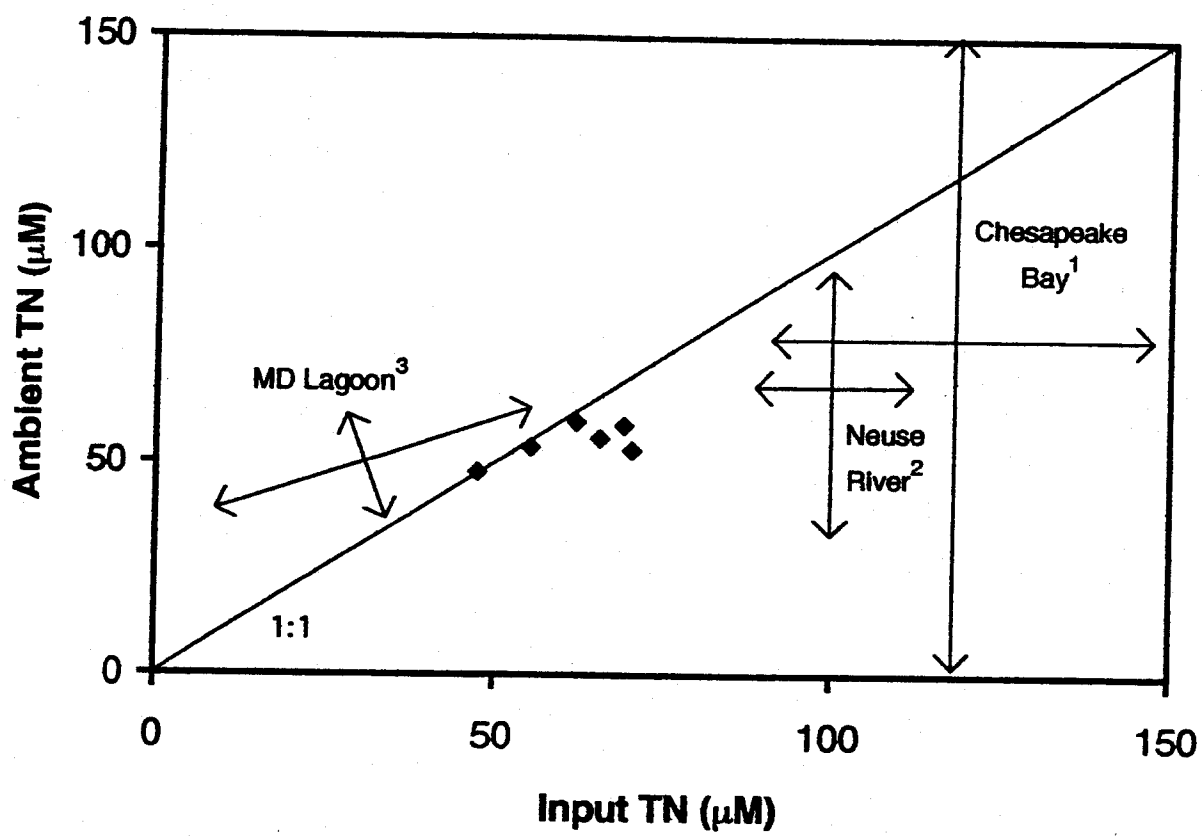


Figure 8

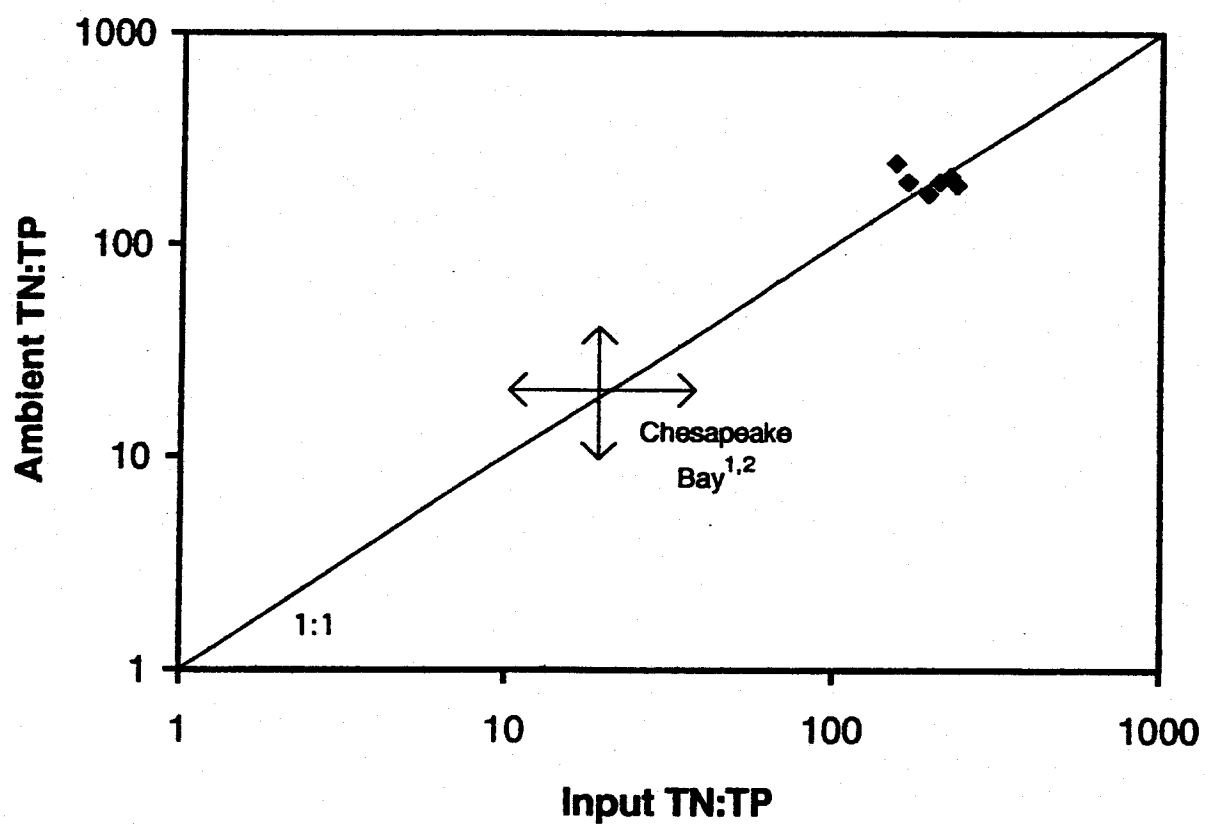


Figure 8

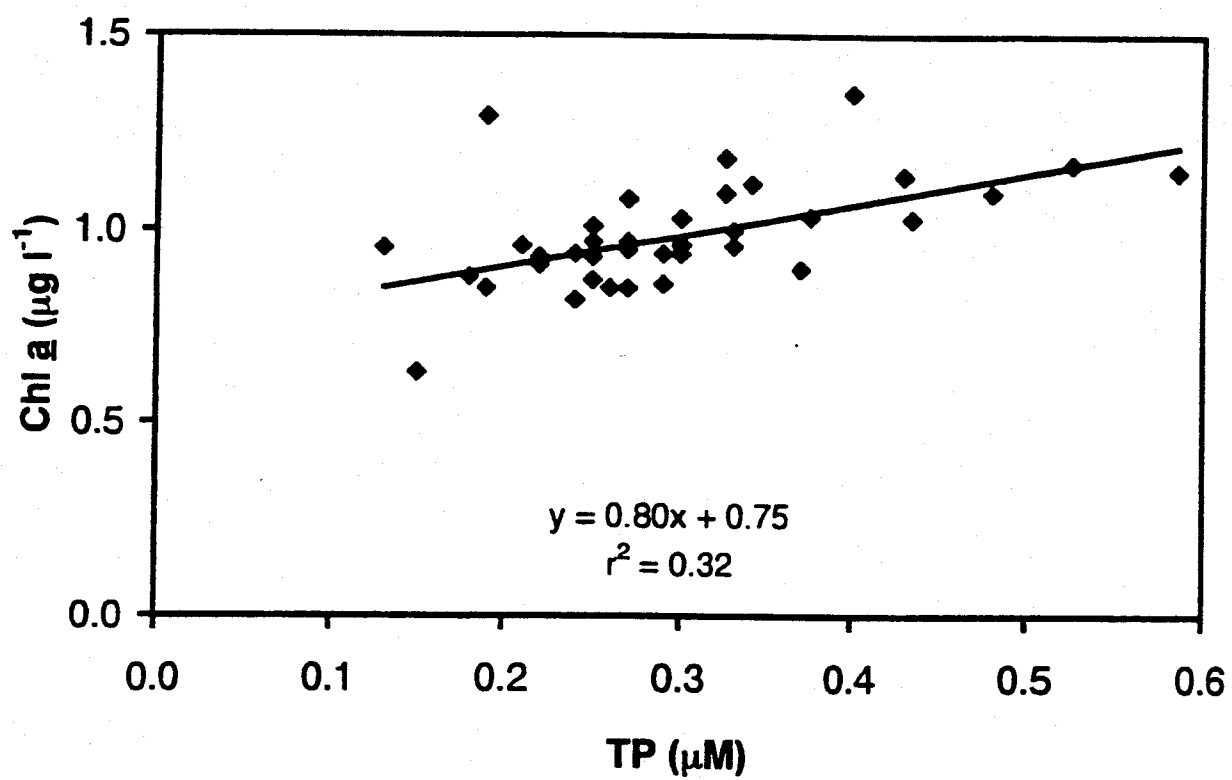


Figure 9

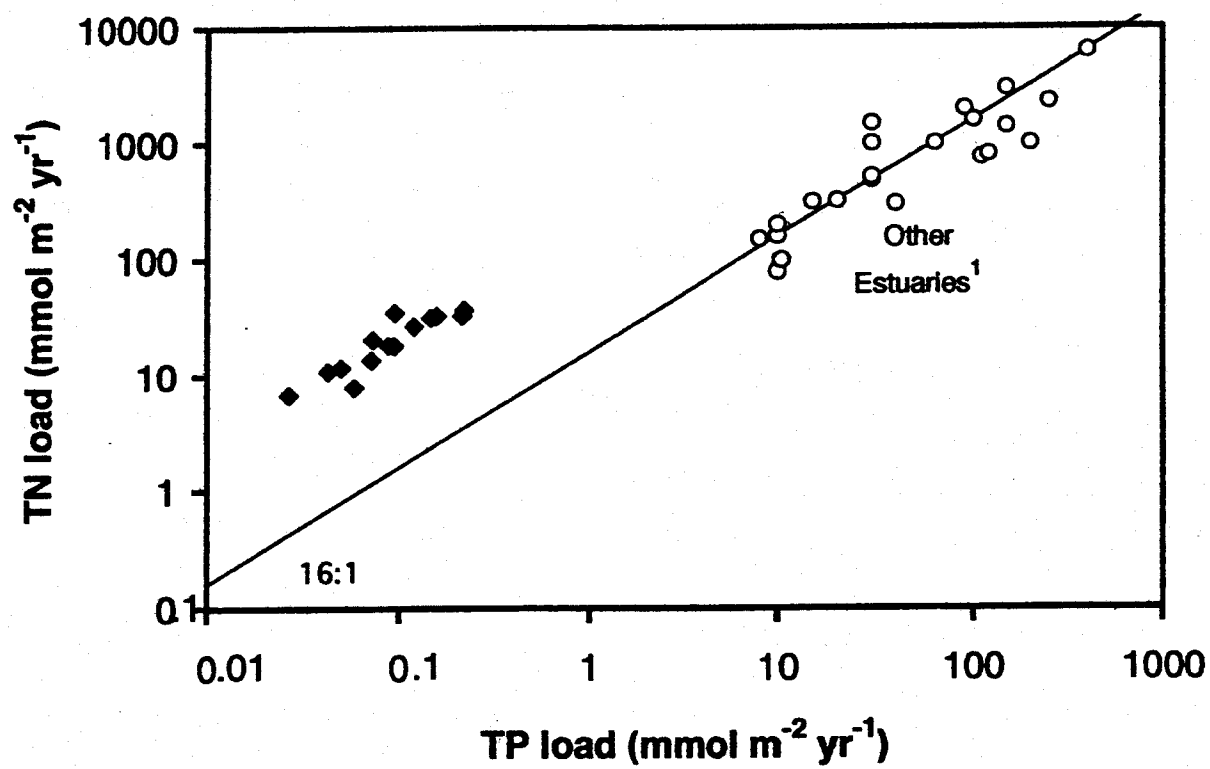
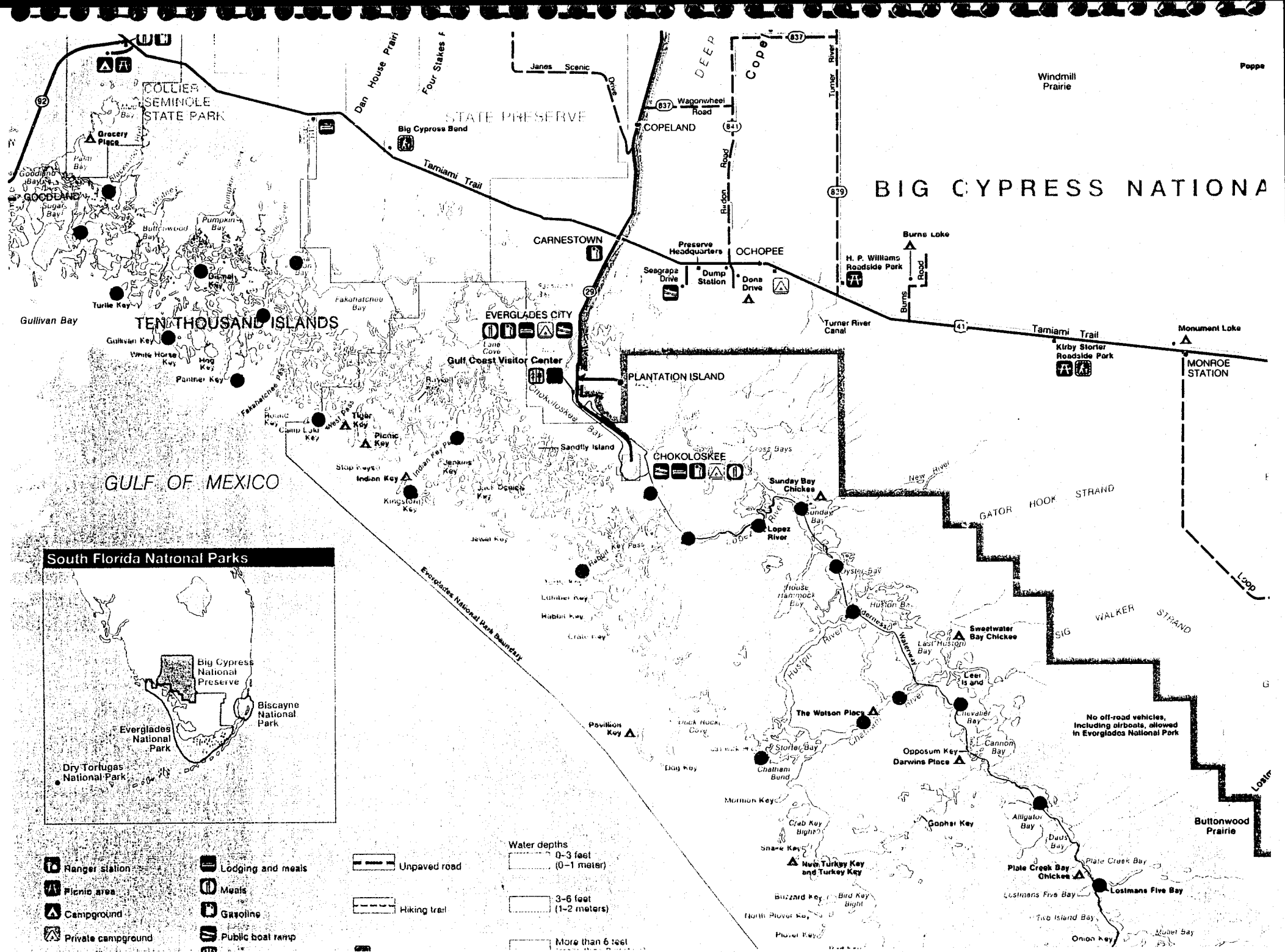


Figure 10

WHITEWATER BAY - TEN THOUSAND ISLANDS, ME.



WHITEWATER BAY - TEN THOUSAND ISLANDS: Spatial Analysis

Table 1: Ten Thousand Islands Station Summary

Station Name	Station Number	Zone	Latitude	Longitude	Period of Record	Surveys
Chokoloskee	51	GI	25 48.450	81 20.970	Sept 94 - Dec 97	43-82
Rabbit Key Pass	52	GI	25 46.200	81 23.000	Sept 94 - Dec 97	43-82
Lopez Bay	53	IWW	25 47.050	81 19.930	Sept 94 - Dec 97	43-82
Lopez River	54	IWW	25 47.130	81 18.550	Sept 94 - Dec 97	43-82
Sunday Bay	55	IWW	25 47.760	81 16.800	Sept 94 - Dec 97	43-82
Huston Bay	56	IWW	25 45.180	81 15.330	Sept 94 - Dec 97	43-82
Upper Chatham River	57	IWW	25 43.050	81 13.830	Sept 94 - Dec 97	43-82
Middle Chatham River	58	IWW	25 42.470	81 14.630	Sept 94 - Dec 97	43-82
Gun Rock Point	59	IWW	25 41.500	81 17.920	Sept 94 - Dec 97	43-82
Oyster Bay	60	IWW	25 46.280	81 15.880	Oct 94 - Dec 97	43-82
Chevelier Bay	61	IWW	25 42.750	81 12.420	Sept 94 - Dec 97	43-82
Alligator Bay	62	IWW	25 40.210	81 10.120	Sept 94 - Dec 97	43-82
Lostman's Five Bay	63	MR	25 38.000	81 08.700	Sept 94 - Dec 97	43-82
Barron River	64	IWW	25 51.196	81 23.602	Sept 94 - Dec 97	43-82
Indian Key Pass	65	GI	25 49.631	81 26.465	Sept 94 - Dec 97	43-82
Indian Key	66	GI	25 48.290	81 27.750	Sept 94 - Dec 97	43-82
West Pass	67	GI	25 49.820	81 30.170	Sept 94 - Dec 97	43-82
Panther Key	68	GI	25 50.960	81 32.530	Sept 94 - Dec 97	43-82
Faka Union Pass	69	GI	25 52.450	81 30.960	Sept 94 - Dec 97	43-82
Faka Union River	70	MR	25 54.000	81 30.960	Sept 94 - Dec 97	43-82
White Horse Key	71	GI	25 52.007	81 34.489	Sept 94 - Dec 97	43-82
Dismal Key	72	GI	25 53.668	81 33.532	Sept 94 - Dec 97	43-82
Gullivan Bay	73	GI	25 52.920	81 36.380	Sept 94 - Dec 97	43-82
Shell Key	74	BLK	25 54.670	81 36.920	Sept 94 - Dec 97	43-82
Blackwater River	75	BLK	25 55.788	81 36.019	Sept 94 - Dec 97	43-82

Influence of coastal geomorphology on the water quality of mangrove
estuaries in the Ten Thousand Islands - Whitewater Bay complex, SW
Florida, USA.

JOSEPH N. BOYER*

RONALD D. JONES

Southeast Environmental Research Program

Florida International University

Miami, FL 33199

*Corresponding Author, 305-348-4076 (Office), 305-348-4096 FAX

boyerj@servax.fiu.edu

Draft of manuscript for submission to Estuarine, Coastal Shelf Science.

ABSTRACT: We apply a multivariate statistical analysis to a 4 year, multiparameter data set in an effort to describe the spatial dependence and inherent variation of water quality patterns in the Ten Thousand Islands - Whitewater Bay area. Principal component analysis of 16 water quality parameters collected monthly resulted in 5 principal components which explained 72.5 % of the variance of the original variables. The "Organic" component (PC_I) was composed of APA, TON, and TOC; the "Dissolved Inorganic N" component (PC_{II}) contained NO_2^- , NH_4^+ , and NO_3^- ; the "Phytoplankton" component (PC_{III}) was made up of TP, Chl *a*, and turbidity; DO and temperature were inversely related (PC_{IV}); and salinity and SRP made up PC_V . A cluster analysis of the mean and SD of PC scores resulted in the spatial aggregation of the 47 fixed stations into 6 zones of similar influence (ZSI) which we defined as: Mangrove Rivers, Whitewater Bay, Gulf Islands, Coot Bay, Blackwater River, and Inland Waterway. Marked differences in physical, chemical, and biological characteristics among ZSI were illustrated by this technique. Comparison of medians and variability of parameter values among ZSI allowed large scale generalizations as to underlying differences in water quality in these regions.

INTRODUCTION

The mangrove estuaries of the Ten Thousand Islands - Whitewater Bay complex (TTI-WWB) on the SW coast of the Florida peninsula comprise a diverse and dynamic ecosystem (Fig. 1). The TTI-WWB mangrove estuaries of the region are highly compartmentalized by geomorphology, making it difficult to study nutrient biogeochemistry using standard schemes of estuarine ecology. Sources of both freshwater and nutrients are difficult to quantify, owing to the non-point source nature of runoff from the Everglades.

As we were interested in understanding the spatial patterns of water quality of the TTI-WWB complex, analysis required the reduction of a complicated data matrix into fewer elements. Multivariate statistical techniques can be used to reduce the number of variables into a smaller set of independent, synthetic variables that capture the variance of the original data set. We previously applied principal component analysis (PCA) and a clustering algorithm to characterize mesoscale variability in Florida Bay (Boyer et al. 1997).

To understand the factors influencing nutrient biogeochemistry in embayments in southwestern Florida, it is important to be able to objectively group stations of similar water quality (as physical and chemical parameters). In this paper, we apply PCA to a 4 year, multiparameter data set in an effort to describe the spatial dependence and inherent variation of water quality patterns in the TTI-WWB complex. This is followed by a cluster analysis which objectively classifies sampling stations in this network into groups with similar water quality for the period of record. 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. It is reasonable to assume that groups of stations with similar water quality are the result of comparable interactions, hence we call these regions zones of similar influence (ZSI). The utility of this approach for further analysis and new hypothesis development are discussed.

METHODS

SITE CHARACTERISTICS

The Ten Thousand Islands - Whitewater Bay area is located on the SW coast of the Florida peninsula between Cape Sable and Cape Romano (Fig 1). The lower portion is composed of mangrove-lined streams and rivers originating from the Shark River Slough in the Everglades. It is a brackish complex that drains into the SW Florida Shelf region of the Gulf of Mexico (hereafter called Shelf). In this region there are >60,000 ha of mangrove forest made up of tall trees (up to 25 m); mainly red (Rhizophora mangle), black (Avicennia germinans) and white (Laguncularia racemosa) mangroves (Smith et al. 1994). The mangrove forest is a continuous band that stretches about 15 km inland from the coast. The bottom of the embayments in this region is largely calcareous mud, with occasional seagrass beds. Oyster bars are common in this area.

A total of 47 stations were situated within the TTI-WWB complex so as to provide a sampling gradient from freshwater to estuary throughout the many rivers in the region (Fig. 1). Stations in WWB were sampled monthly from Oct. 1992 - Sept. 1997; the period of record (POR) for TTI was Sept. 1994 - Sept. 1997. Four days were required for each sampling event.

ANALYTICAL METHODS

Surface salinity and temperature were measured using a combination salinity-conductivity-temperature probe (Orion model 140). Dissolved oxygen (DO, mg l⁻¹) was measured 10 cm below the surface using an oxygen electrode (Orion model 840) corrected for salinity and temperature. DO saturation (DO_{sat} in %) was calculated using the equations of Garcia and Gordon (1992).

Duplicate, unfiltered water samples were collected from 10 cm below the surface using acetone-washed and sample rinsed 12 ml HDPE bottles and kept at ambient temperature in the dark during transport. Duplicate water samples for dissolved nutrient analysis were collected using acid-washed and sample rinsed 150 ml syringes. Samples were filtered (25 mm glass fiber GF/F) by hand into acetone-washed and sample rinsed 60 ml HDPE bottles, which were capped and immediately placed on ice in the dark for transport. The wet filters, used for chlorophyll *a* (Chl *a*) analysis, were placed in 1.8 ml plastic centrifuge tubes to which 1.5 ml of 90% acetone was added (Strickland and Parsons 1972); they were then capped and put into a dark bottle on ice for transport.

Unfiltered water samples were analyzed for total organic carbon (TOC), total nitrogen (TN), total phosphorus (TP), 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 CO₂-free air. TN was measured using an ANTEK 7000N Nitrogen Analyzer using O₂ as carrier gas instead of argon to promote complete recovery of the nitrogen in the water samples (Jones and Frankovich in press). TP was determined using a dry ashing, acid hydrolysis technique (Solórzano and Sharp 1980). The APA assay measures the activity of alkaline phosphatase, an enzyme used by bacteria to mineralize phosphate from organic compounds. The assay is performed by adding a known concentration of an organic phosphate compound (methylfluorescein phosphate) to an unfiltered water sample. Alkaline phosphatase in the water sample cleaves the phosphate, leaving methylfluorescein, a highly fluorescent compound. The fluorescence of initial and 2 hr incubations were measured using a Gilford Fluoro

IV Spectrofluorometer (excitation = 430 nm, emission = 507 nm) and subtracted to give APA ($\mu\text{M h}^{-1}$). 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 ammonium (NH_4^+) on a four channel autoanalyzer (Alpkem model RFA 300). Filters for Chl *a* content ($\mu\text{g l}^{-1}$) 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.

Some parameters were not measured directly, but were calculated by difference. Nitrate (NO_3^-) was calculated as $\text{NO}_x^- - \text{NO}_2^-$. Dissolved inorganic nitrogen (DIN) was calculated as $\text{NO}_x^- + \text{NH}_4^+$. Total organic nitrogen (TON) was defined as $\text{TN} - \text{DIN}$. All concentrations are reported as μM unless noted. All N:P ratios calculated and discussed in this paper are on a molar basis.

STATISTICAL ANALYSES

In order to assess the underlying patterns in the distribution of the measured parameters, we followed the procedure of Boyer et al. (1997). Briefly, principal component analysis (PCA) was used to extract 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 over the POR for each station were then used as independent variables in a cluster analysis in order to aggregate stations into zones of similar influence (ZSI). The purpose of this analysis was to collapse the number of stations into a few groups which could then be analyzed in more detail.

Once stations were grouped by cluster analysis, statistical analysis of the water chemistry among ZSI was possible (see box-and-whiskers plots, Figs. 2-5). 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. The box-and-whisker plot is a powerful statistic as it shows the median, range, distribution of the data as well as serving as a graphical, nonparametric ANOVA. In addition, differences in parameters among ZSI were quantified using Kruskal-Wallis test with significance set at $P < 0.05$.

RESULTS

RANGES AND MEDIANS OF DATA

Large ranges in most measured parameters were the norm owing to the wide spatial and temporal sampling plan (Table 1). Medians are reported as the nonparametric statistic of central tendency due to the skewed nature of most water chemistry data (see Christian et al. 1991). Overall, the region was warm and hyposaline, with a median temperature of 26.6°C and a median salinity of 12.9 ppt. The median DO was 5.9 mg l^{-1} , or ~77 % of saturation. DIN concentrations were a small fraction of the TN pool (4%) with TON making up the bulk. NH_4^+ was the

dominant DIN species in almost all of the samples (57 % of DIN). SRP concentrations were low ($0.09 \mu\text{M}$) and comprised only 10% of the TP pool ($0.92 \mu\text{M}$). Chl *a* concentrations were also low overall ($2.7 \mu\text{g l}^{-1}$) but ranged from 0.12 to $45.1 \mu\text{g l}^{-1}$. The TN:TP ratio suggested a strong P limitation of the water column; the median TN:TP = 61 but ranged from 10-157.

PRINCIPAL COMPONENT ANALYSIS

PCA identified five composite variables (hereafter called PC_I , PC_{II} , 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 five separate modes of variation in the data. PC_I had high factor loadings for APA, TON, and TOC and was therefore designated as the "Organic" component. PC_{II} was composed of NO_2^- , NH_4^+ , and NO_3^- and was called the "Dissolved Inorganic N (DIN)" component. TP, Chl *a*, and turbidity were highly correlated in the "Phytoplankton" PC_{III} component. PC_{IV} included negatively correlated temperature and DO concentration. Finally, salinity and SRP were included in PC_V . These five principal components accounted for 72.5 % of the total variance of the original variables.

CLUSTER ANALYSIS

A k-means clustering algorithm, using the mean and SD of the five factor scores of each station, objectively classified the 47 sampling sites into 6 groups having similar water quality, or zones of similar influence (ZSI, Fig. 1). The first cluster was composed of 13 stations in and around the Shark, Harney, Broad, and Lostmans Rivers and is called the "Mangrove River" group. This cluster also included a sampling station just off the Faka Union Canal. The second cluster was made up of the 8 stations enclosed within Whitewater Bay proper (called "Whitewater Bay"). Twelve stations situated mostly in and around the coastal islands of TTI-WWB formed the "Gulf Island" group. As in a previous analysis of Florida Bay - Whitewater Bay (Boyer et al. 1997), the water quality characteristics at the Coot Bay site were sufficiently different so as to be a cluster of its own. Coot Bay is a small, almost completely enclosed bay that was connected to Florida Bay by the Buttonwood canal dug through the mangroves in 1957 (Tabb et al. 1962). In 1982 the canal was plugged at the Florida Bay end, hydraulically isolating it once again from both Whitewater and Florida Bays. Because of its small area and isolated outlier status, Coot Bay will not be included in further discussions. The next cluster contained the northernmost 2 stations in the Blackwater River estuary ("Blackwater"). Finally, the "Inland Waterway" ZSI included 11 stations distributed throughout the inside passage as well as the Chatham River and, oddly, our station off Everglades City.

WATER QUALITY CHARACTERISTICS AMONG ZSI

The "Organic" component (PC_I), composed of APA, TON, and TOC, explained 16% of the variance in the original data set (Table 2). The similarity in magnitude of these 3 parameters among ZSI is striking (Fig. 2). It is clear that APA as well as TON and TOC concentrations were highest in Whitewater Bay > Mangrove River > Inland Waterway > Gulf Islands and Blackwater River. These differences among ZSI were all statistically significant. It is interesting to note the northwards decreasing gradient of TON and TOC along the coast.

The water quality parameters composing the "DIN" component (PC_{II}) were NO_2^- , NH_4^+ , and NO_3^- which explained 16.1 % of the variance (Table 2). Small but significant differences in DIN species among ZSI were observed (Fig. 3). NO_2^- concentrations were highest in the Blackwater River and Mangrove Rivers (0.22 and 0.20 μM), lowest in Whitewater Bay (0.14 μM) although it had the greatest range (0.01-5.33 μM), with the other ZSI being intermediate. Median NH_4^+ concentrations in the Blackwater River and Mangrove Rivers (1.48 and 1.35 μM) were significantly higher than for all other ZSI. For NO_3^- , the Mangrove Rivers were significantly higher than the other zones (1.19 μM), although Whitewater Bay had the greatest range (0.0-19.7 μM).

TP, Chl *a*, and turbidity were the three elements which made up the "Phytoplankton" component (PC_{III}) and explained 15.0 % of the variance (Table 2). Median TP in the Blackwater River (1.91 μM) was significantly greater than any other ZSI while the Mangrove Rivers (0.80 μM) and Whitewater Bay (0.62 μM) were the lowest (Fig. 4). Chl *a* concentrations in the Inland Waterway (3.66 $\mu g\ l^{-1}$) and Blackwater River (3.18 $\mu g\ l^{-1}$) were significantly higher than the other zones. As with TP, turbidity followed the same North-South gradient of being highest in Blackwater River (9.45 NTU), intermediate in the Gulf Islands (6.68 NTU) and Inland Waterway (5.70 NTU) and lowest in Whitewater Bay and Mangrove Rivers (4.45 & 3.15 NTU).

DO concentrations in Whitewater Bay (6.8 $mg\ l^{-1}$) were significantly higher than the other ZSI (Fig. 5) with the Mangrove Rivers exhibiting the lowest (5.1 $mg\ l^{-1}$). Median water temperature was not significantly different among zones. DO saturation (DO_{sat} , %) followed a slightly different trend than DO ($mg\ l^{-1}$), mostly as a function of salinity. DO_{sat} in the Mangrove Rivers (63.1 %) was significantly lower than in the Inland Waterway (76.0 %) which in turn was lower than the other ZSI (80-86 %).

There were large variations in salinity among the ZSI and almost all were significantly different from each other (Fig. 6). Salinity was highest in Blackwater River (31.7 ppt) > Gulf Islands (27.2 ppt) > Inland Waterway and Whitewater Bay (10.8 and 10.2 ppt) > Mangrove Rivers (3.7 ppt). Both the Inland Waterway and Mangrove Rivers had large ranges in salinity (0.0-37.9 ppt) as a function of their more estuarine nature. SRP concentrations were low in most of the zones (~0.07 μM) except for the Gulf Islands which was higher (0.30 μM) and the Blackwater River which was 10 times higher than the other zones (0.73 μM). This northwards increasing gradient in SRP mirrored the TP gradient (Fig. 4).

The median TN:TP ratio of the TTI-WWB complex decreased significantly in a northerly direction along the coast (Fig. 6). Blackwater River had the lowest TN:TP (17.3), increasing to 105 in Whitewater Bay. This gradient in TN:TP ratio was due to both a decrease in TP concentration (Fig. 4) as well as an increase in TON (Fig. 2).

DISCUSSION

One of the purposes of any monitoring program should be to use the data gained by routine sampling to extend our understanding of the system by developing new hypotheses as to the underlying processes which drive it. Much inference into the behavior of Ten Thousand Islands - Whitewater Bay can be made from the observed magnitude and distribution of water quality parameters.

The process of using principal component analysis in combination with multivariate cluster analysis has been shown to be a useful method of aggregating spatially distributed stations into geographical zones possessing similar water quality characteristics. This method has proven extremely useful for monitoring programs as it objectively classifies ecosystems into functionally distinct zones (Boyer et al. 1997). Using this approach, the TTI-WWB complex was partitioned into 6 distinct ZSI: Blackwater River, Gulf Islands, Inland Waterway, Mangrove Rivers, Whitewater Bay, and Coot Bay. Marked differences in physical, chemical, and biological characteristics among ZSI were illustrated by this technique.

ACKNOWLEDGMENTS

We thank Pete Lorenzo, Tom Frankovich, Jeff Absten, and all the other field and laboratory technicians involved with this project over the years. This study was supported by grants from the South Florida Water Management District (C-7919) and Everglades National Park (CA5280-2-9017). This is contribution #xx of the Southeast Environmental Research Program at Florida International University.

LITERATURE CITED

- BOTO, K. G. AND A. I. ROBERTSON. 1990. The relationship between nitrogen fixation and tidal exports of nitrogen in a tropical mangrove system. Estuarine, Coastal and Shelf Science 31:531-540.
- BOYER, J. N., J. W. FOURQUREAN, AND R. D. JONES. 1997. Spatial trends in water chemistry of Florida Bay and Whitewater Bay: Zones of similar influence (ZSI). Estuaries 20:743-758.
- CHEN, R. AND R. R. TWILLEY. In review. Patterns of mangrove forest structure associated with soil properties in the Shark River estuary. Oecologia.
- CHRISTIAN, R. R., J. N. BOYER, D. W. STANLEY, AND W. M. RIZZO. 1991. Multi-year distribution patterns of nutrients in the Neuse River Estuary, North Carolina. Marine Ecology Progress Series 71:259-274.
- GARCIA, H. E., AND L. I. GORDON. 1992. Oxygen solubility in seawater: Better fitting equations. Limnology and Oceanography 37:1307-1312.
- JONES, R. D., AND T. A. FRANKOVICH. 1997. A rapid, precise, and sensitive method for the determination of total nitrogen in natural waters. Marine Chemistry (in press).
- OVERLAND, J. E. AND R. W. PREISENDORFER. 1982. A significance test for principal components applied to cyclone climatology. Monthly Weather Review 110:1-4.
- SMITH, T. J. III, M. B. ROBBLEE, H. R. WANLESS, AND T. W. DOYLE. 1994. Mangroves, hurricanes, and lightning strikes. Bioscience 44:256-262.
- SOLORZANO, L., AND J. H. SHARP. 1980. Determination of total dissolved phosphorus and particulate phosphorus in natural waters. Limnology and Oceanography 25:754-758.
- STRICKLAND, J. D. H., AND T. R. PARSONS. 1972. A practical handbook of seawater analysis. Bulletin of the Fisheries Research Board of Canada 167:107-112.
- TABB, D. C., D. L. DUBROW, AND R. B. MANNING. 1962. The ecology of northern Florida Bay and adjacent estuaries. Technical Series No. 39, Board of Conservation, State of Florida, Miami, FL.

Table 1. Summary statistics for all measured parameters, 1992-97. MAD = median absolute deviation; BD = below detection.

Parameter	Median	MAD	Min.	Max.	n
Temp. (°C)	26.6	2.9	12.5	32.7	2122
Salinity (ppt)	12.9	10.4	0.0	37.9	2122
DO (mg l ⁻¹)	5.9	1.1	0.8	12.1	2122
NO ₃ ⁻ (μM)	0.67	0.56	BD	19.2	2122
NO ₂ ⁻ (μM)	0.18	0.08	BD	7.60	2122
NH ₄ ⁺ (μM)	1.14	0.64	0.03	74.7	2122
TON (μM)	50.1	13.6	9.26	213.5	2121
SRP (μM)	0.09	0.07	BD	2.14	2121
TP (μM)	0.92	0.32	0.02	3.61	2114
TOC (μM)	1093	338.5	317.1	5334	2120
APA (μM h ⁻¹)	0.18	0.15	0.01	4.39	2119
Chl <u>a</u> (μg l ⁻¹)	2.71	1.32	0.12	45.1	2120
Turbidity (NTU)	4.90	2.55	0.20	107.8	2120

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

Parameter	Principal Component				
	PC _I	PC _{II}	PC _{III}	PC _{IV}	PC _V
APA	0.81	-0.05	0.12	-0.31	0.12
TON	0.79	-0.01	0.02	0.17	-0.34
TOC	0.70	0.18	-0.05	0.17	-0.32
NO ₂ ⁻	0.06	0.87	-0.01	-0.08	0.07
NH ₄ ⁺	0.11	0.77	-0.01	0.02	0.07
NO ₃ ⁻	-0.13	0.77	0.01	-0.02	-0.21
TP	-0.17	0.08	0.84	0.29	0.12
Chl _a	0.19	-0.12	0.78	-0.13	-0.18
Turbidity	0.06	0.01	0.69	-0.27	0.20
DO	0.16	-0.05	0.09	-0.89	0.03
Temperature	0.25	-0.17	-0.01	0.78	0.21
Salinity	-0.20	-0.10	0.01	0.07	0.88
SRP	-0.35	0.23	0.37	0.22	0.55
%Total Variation	16.3	16.1	15.0	13.7	11.4

Cumulative Variance Explained = 72.5 %

Figure Legends

Fig 1. Map of sampling stations in Ten Thousand Islands - Whitewater Bay complex showing zones of similar influence (ZSI) from cluster analysis of mean and SD of five principal component scores. The ZSI are: Mangrove Rivers (black), Whitewater Bay (magenta), Gulf Islands (red), Coot Bay (light blue), Blackwater River (dark blue), and Inland Waterway (green).

Fig. 2. Box-and-whisker plots of PC_I factors: alkaline phosphatase activity (APA; $\mu\text{M h}^{-1}$), total organic nitrogen (TON; μM), and total organic carbon (TOC; μM) where BLK = Blackwater River, GI = Gulf Islands, IW = Inland Waterway, MR = Mangrove Rivers, and WB = Whitewater Bay. The center horizontal line in the box is the median, 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 is the 95 % confidence interval of the median. When notches between boxes do not overlap, the medians are significantly different.

Fig. 3. Box-and whisker plots of PC_{II} factors: NO_2^- (μM), NH_4^+ (μM), and NO_3^- (μM) with legend as in Fig. 2.

Fig. 4. Box-and-whisker plots of PC_{III} factors: total phosphorus (TP; μM), chlorophyll *a* (Chl*a*; $\mu\text{g l}^{-1}$), and turbidity (NTU) with legend as in Fig. 2.

Fig. 5. Box-and-whisker plots of PC_{IV} factors: dissolved oxygen (DO; mg l^{-1}), and temperature ($^{\circ}\text{C}$) as well as DO saturation (DO_{sat} ; %) with legend as in Fig. 2.

Fig. 6. Box-and-whisker plots of PC_V factors: salinity (ppt), and soluble reactive phosphorus (SRP; μM). Also includes plot of molar TN:TP ratio with legend as in Fig. 2.

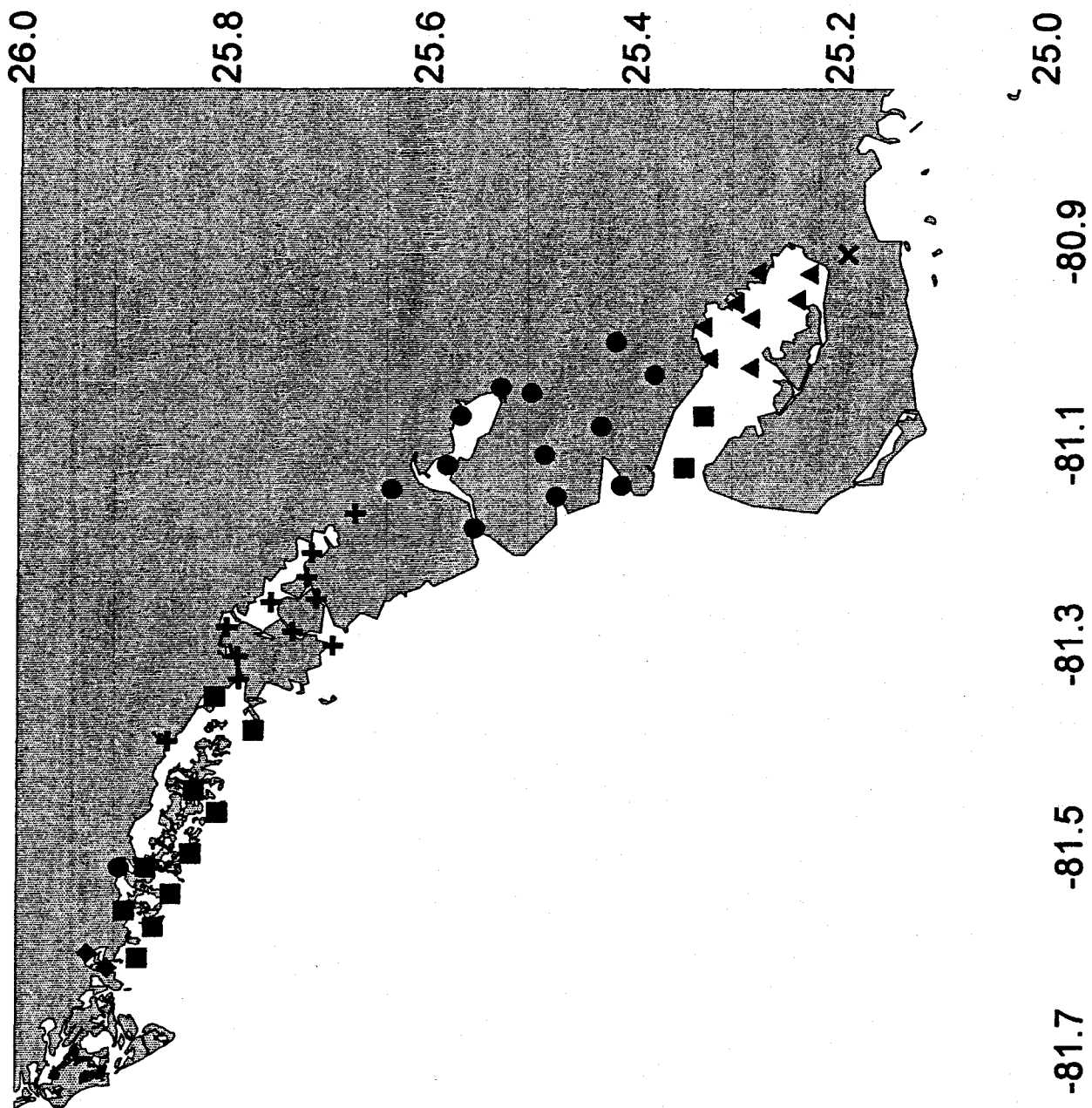


Figure 1

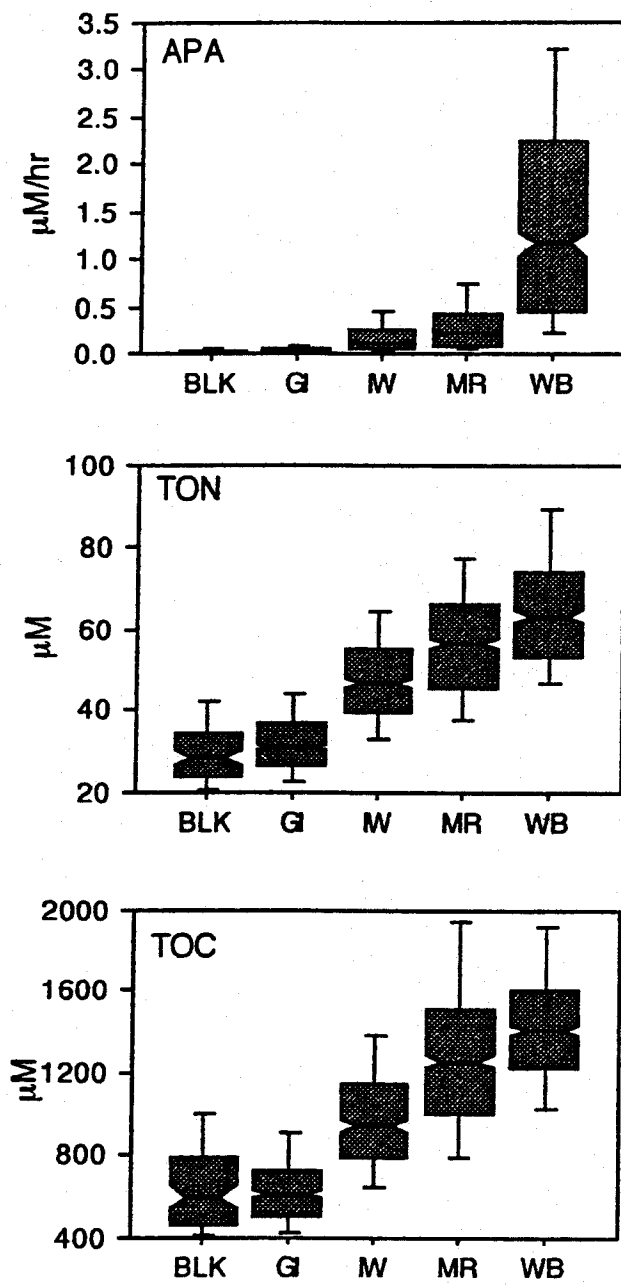


Figure 2

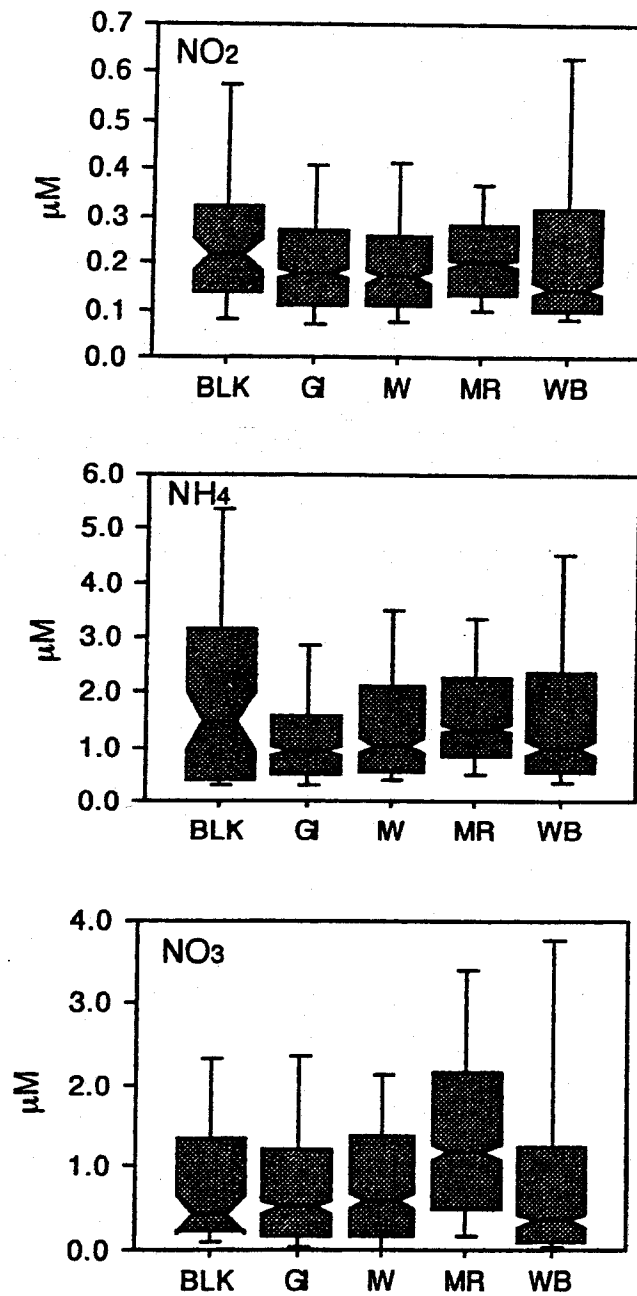


Figure 3

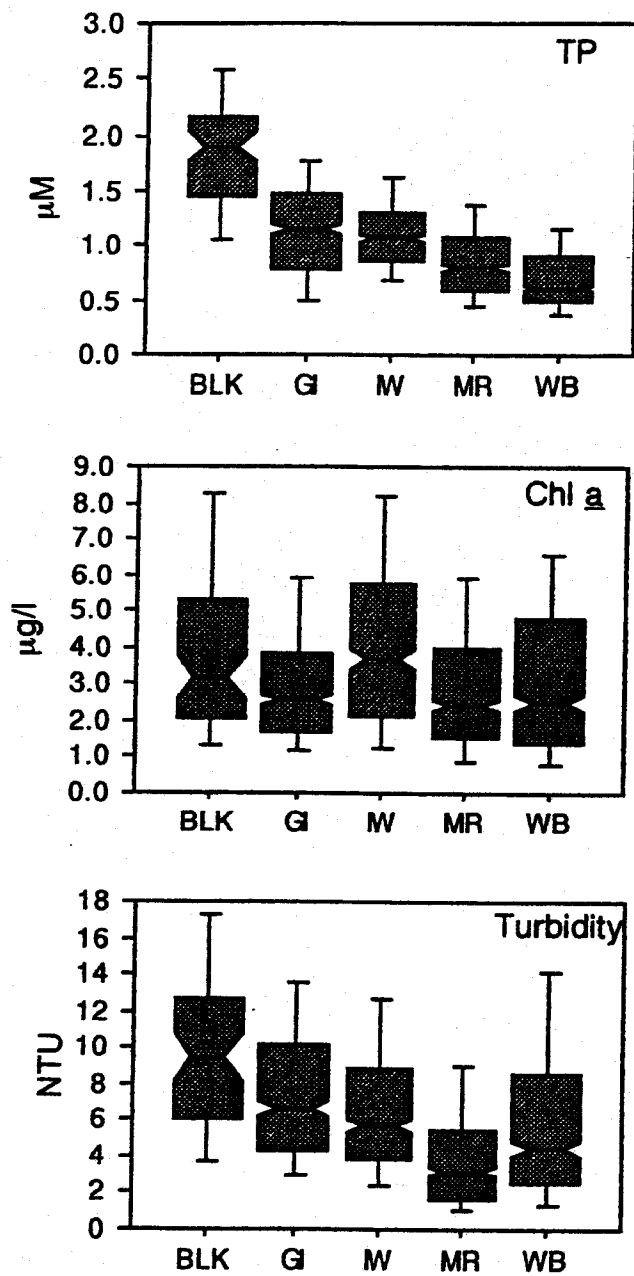


Figure 4

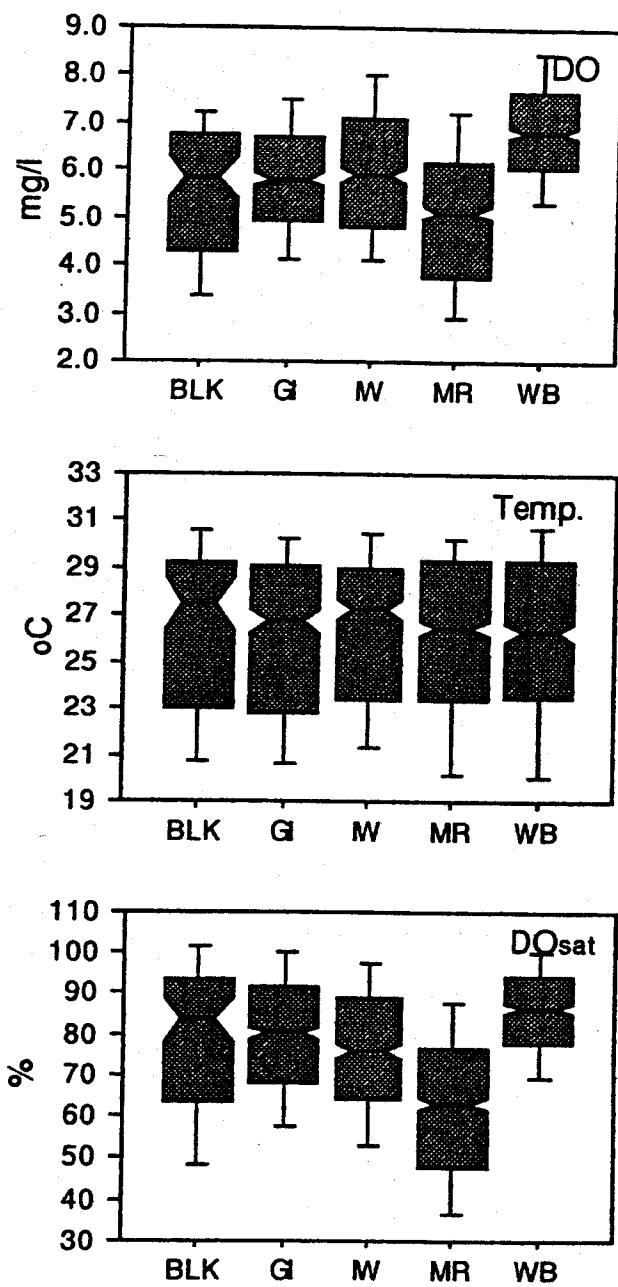


Figure 5

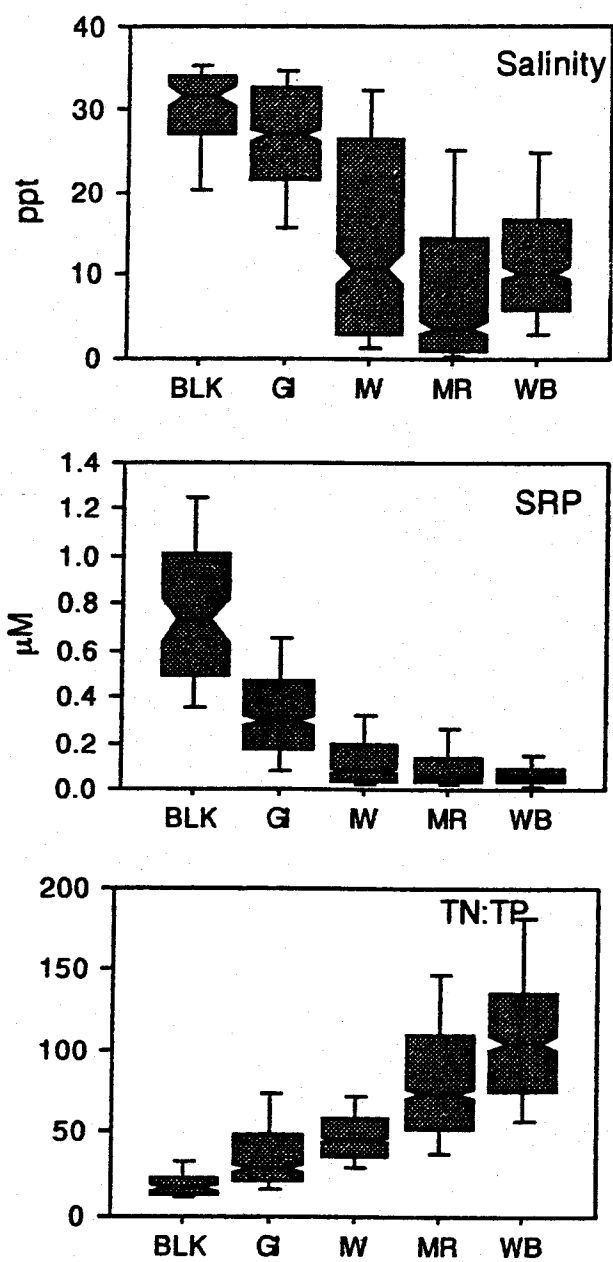
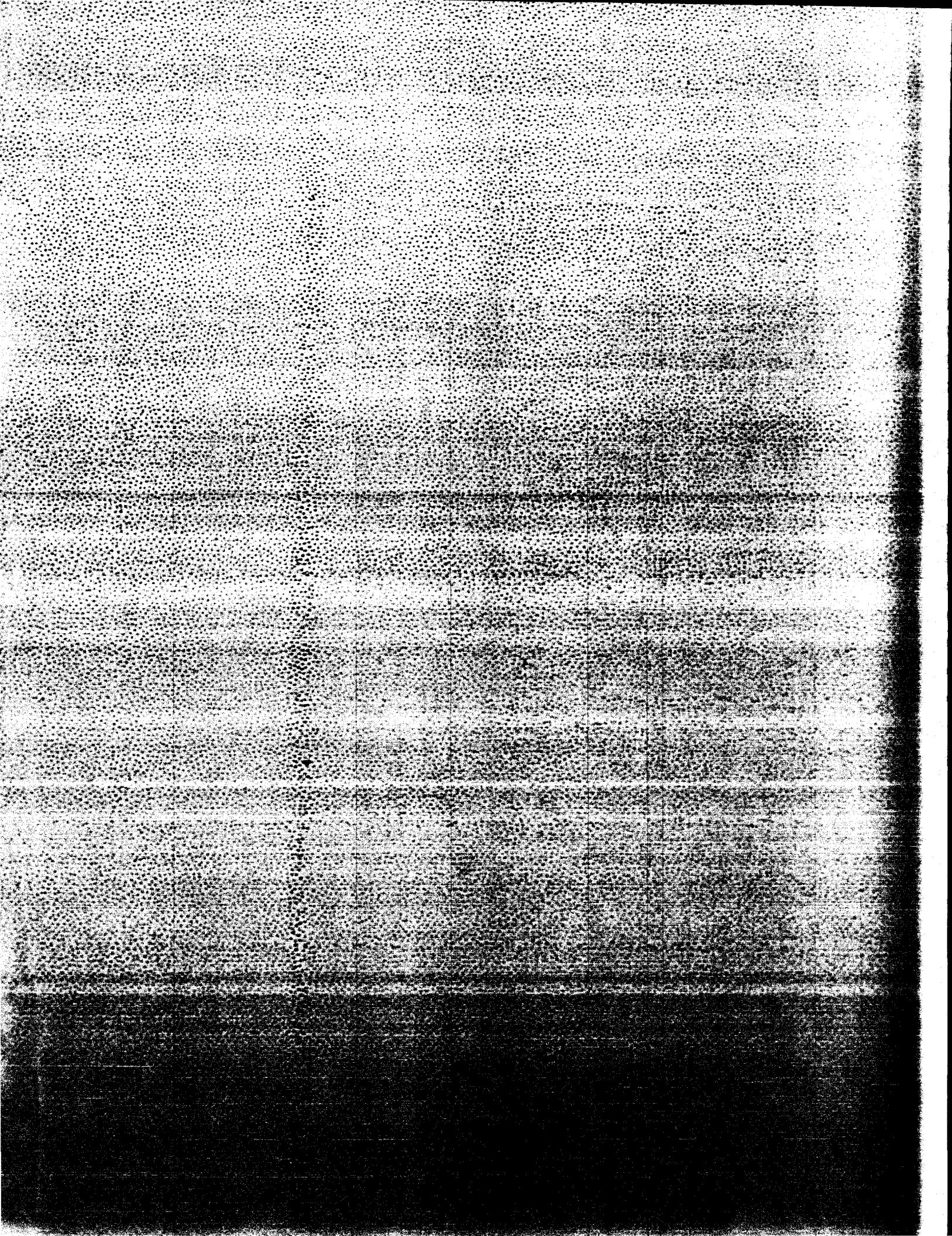
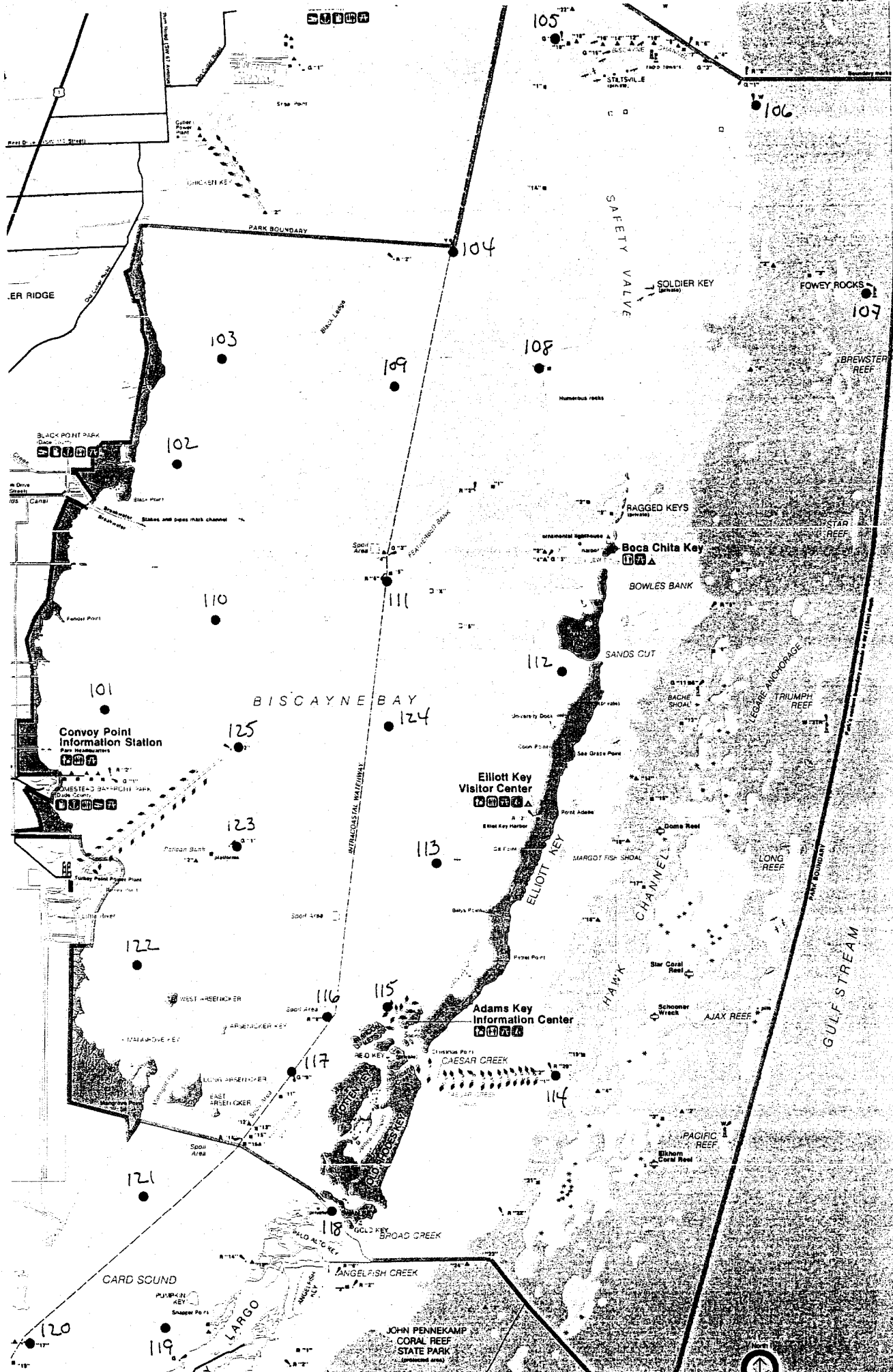


Figure 6



BISCAYNE BAY Map



BISCAYNE BAY: Spatial Analysis

Table 1: Biscayne Bay Station Summary

Station Name	Station Number	Zone	Latitude	Longitude	Period of Record	Surveys
Convoy Point	101	AS	25.4783	80.3208	Sept 93 - Dec 97	31-82
Black Point	102	AS	25.5458	80.2947	Sept 93 - Dec 97	31-82
Near Black Ledge	103	IS	25.5733	80.2867	Sept 93 - Dec 97	31-82
BNP Marker "C"	104	MAIN	25.6017	80.2208	Sept 93 - Dec 97	31-82
Bisc. Channel, G-21	105	MAIN	25.6542	80.1867	Sept 93 - May 96	31-63
Bisc. Channel, FWT	106	OCHAN	25.6342	80.1300	Sept 93 - May 96	31-63
Fowey Rocks	107	MAIN	25.5900	80.1000	Sept 93 - May 96	31-63
Marker G-1B	108	MAIN	25.5692	80.1925	Sept 93 - Dec 97	31-82
North Midbay	109	MAIN	25.5642	80.2350	Sept 93 - Dec 97	31-82
Fender Point	110	IS	25.5050	80.2875	Sept 93 - Dec 97	31-82
Featherbed Bank	111	MAIN	25.5158	80.2400	Sept 93 - Dec 97	31-82
Sands Cut	112	MAIN	25.4883	80.1883	Sept 93 - Dec 97	31-82
Elliott Key	113	MAIN	25.4417	80.2233	Sept 93 - Dec 97	31-82
Caesar Creek, R-20	114	OCHAN	25.3850	80.1917	Sept 93 - May 96	31-63
Adams Key	115	MAIN	25.4042	80.2408	Sept 93 - May 96	31-63
Rubicon Keys	116	MAIN	25.4000	80.2550	Sept 93 - Dec 97	31-82
Totten Key	117	MAIN	25.3850	80.2650	Sept 93 - May 96	31-63
Broad Creek	118	MAIN	25.3483	80.2550	Sept 93 - May 96	31-63
Pumpkin Key	119	SCARD	25.3183	80.3033	Sept 93 - May 96	31-63
Card Bank, G-17	120	SCARD	25.3142	80.3433	Sept 93 - May 96	31-63
North Card Sound	121	SCARD	25.3550	80.2917	Sept 93 - Dec 97	31-82
West Arsenicker	122	IS	25.4202	80.3108	Sept 93 - Dec 97	31-82
Pelican Bank	123	MAIN	25.4450	80.2833	Sept 93 - Dec 97	31-82
South Midbay	124	MAIN	25.4725	80.2333	Sept 93 - Dec 97	31-82
Turkey Point Channel	125	TP	25.4700	80.2833	Sept 93 - May 96	31-63
BNP Marker "B"	126	MAIN	25.6717	80.2050	June 96 - Dec 97	64-82
Shoal Point	127	IS	25.6300	80.2500	June 96 - Dec 97	64-82
Matheson Beach	128	IS	25.6883	80.2333	June 96 - Dec 97	64-82
Marker G-71	129	MAIN	25.7367	80.1850	June 96 - Dec 97	64-82
South Dodge Island	130	NBAY	25.7633	80.1717	June 96 - Dec 97	64-82
North Venetian Basin	131	NBAY	25.8000	80.1667	June 96 - Dec 97	64-82
North I-195 Basin	132	NBAY	25.8167	80.1667	June 96 - Dec 97	64-82
North Normandy Isle	133	NBAY	25.8667	80.1500	June 96 - Dec 97	64-82
Oleta River Park	134	NBAY	25.9050	80.1333	June 96 - Dec 97	64-82
South Card Sound	135	SCARD	25.3167	80.3167	June 96 - Dec 97	64-82

PRINCIPAL COMPONENT ANALYSIS

PCA identified five composite variables (hereafter called PC_I, PC_{II}, 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 1), indicate five separate modes of variation in the data. PC_I had high factor loadings for NO₃, NO₂, NH₄, TP and salinity. Salinity was negatively related to these parameters suggesting that this PC be called the "Freshwater Source" component. PC_{II} was composed TON, APA, and TOC making it the "Organic" component. PC_{III} included the expected inverse relationship of temperature and DO concentration. The PC_{IV} group included Chl *a* and SRP ("Phytoplankton"), implying a tight coupling between phytoplankton and SRP availability. Finally, turbidity was the only parameter included in PC_V. These five principal components accounted for 69.1 % of the total variance of the original variables.

CLUSTER ANALYSIS

A k-means clustering algorithm, using the mean and SD of the five factor scores of each station, objectively classified the original 25 sampling sites into 7 groups having similar water quality, or zones of similar influence (ZSI, Fig. 1). The first cluster was composed of 2 stations closest to the shore in the south Bay; they were called the "Alongshore" group. The second cluster was made up of the 5 stations farther from the coast called "Inshore". Thirteen stations situated mostly in the bay proper were called the "Main Bay" group. The next cluster contained the 3 stations situated in areas of great tidal exchange ("Ocean Channel"). Two stations in Card Sound grouped together "Card Sound". Finally, the "Turkey Point" station comprised its own cluster. As mentioned previously, 10 stations were selected for their status as being either redundant (as in some of the Main Bay stations) or as outliers (Turkey Point and the Ocean Channel sites) and redistributed throughout the Bay to provide us with more complete coverage. For purposes of this report, the stations moved into the area north of the Rickenbacker Causeway (Fig. 2) will be defined as a distinct cluster ("North Bay") and discussed below.

WATER QUALITY CHARACTERISTICS AMONG ZSI

The nutrient and salinity parameters composing the "Freshwater Source" component (PC_I) explained 24.3 % of the variance (Table 1). It is clear that there is a gradient of increasing salinity with decreasing nutrient concentration with distance from the west coast of the Bay (Fig. 3). For Alongshore, Inshore, and Main Bay clusters, highest concentrations of NO₃, NO₂, NH₄, and TP were observed in the Alongshore stations. North Bay showed NH₄ levels comparable to the high concentrations seen Alongshore but had a higher median salinity. In addition, North Bay had the highest median TP concentration of any ZSI. Card Sound had relatively high NH₄ concentration

This section presents a preliminary analysis and will be repeated as more years of data are collected.

STATISTICAL ANALYSES

In order to assess the underlying patterns in the distribution of the measured parameters, we followed the procedure of Boyer et al. (1997). Briefly, principal component analysis (PCA) was used to extract 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 over the period of record (POR) for each station were then used as independent variables in a cluster analysis in order to aggregate stations into zones of similar influence (ZSI). The purpose of this analysis was to collapse the number of stations into a few groups which could then be analyzed in more detail.

Once stations were grouped by cluster analysis, statistical analysis of the water chemistry among ZSI was possible (see box-and-whiskers plots, Figs. 3-6). 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. The box-and-whisker plot is a powerful statistic as it shows the median, range, distribution of the data as well as serving as a graphical, nonparametric ANOVA. In addition, differences in parameters among ZSI were quantified using Kruskal-Wallis test with significance set at $P < 0.05$.

RESULTS

RANGES AND MEDIANS OF DATA

Large ranges in most measured parameters were the norm owing to the wide spatial and temporal sampling plan (Table 1). Medians are reported as the nonparametric statistic of central tendency due to the skewed nature of most water chemistry data. Overall, Biscayne Bay was warm (median temperature of 27.3°C) with a near seawater salinity (33.2 ppt). The median DO was 6.3 mg l⁻¹, or 92% of saturation. DIN concentrations were a small fraction of the TN pool (~10%) with TON making up the bulk. NH₄ was the dominant DIN species in almost all of the samples (56% of DIN). SRP concentrations were low (<0.001 ppm) and comprised <10% of the TP pool (0.005 ppm). Chl *a* concentrations were also very low overall (0.28 µg l⁻¹) but ranged from 0.04 to 5.4 µg l⁻¹. The TN:TP ratio ranged from 19-657 with the median of 122 suggesting a very strong and consistent *P* limitation of the water column.

relative to the other nutrients included in PC_I . Some of this may be attributed to the long water residence time of this basin as evidence by near ocean salinities.

The "Organic" component (PC_{II}), composed of TON, APA, and TOC, explained 14% of the variance in the original data set (Table 1). The similarity in magnitude of these 3 parameters among ZSI is striking (Fig. 4). It is clear that APA as well as TON and TOC concentrations were highest in Alongshore > Inshore > Main Bay, denoting a freshwater source. It is interesting to note the northwards decreasing gradient of TON and TOC along the coast.

DO concentrations decreased with distance from the west coast (Fig. 5). Part of this is due to increases in median salinity. DO saturation (%) showed a much smaller decline 99.3, 93.7, and 92.1 for Alongshore, Inshore and Main Bay respectively. DO was lowest in the North Bay zone (5.9 mg l^{-1} or 86.9%). Median water temperature was not significantly different among zones.

SRP and Chl a were the two elements which made up the "Phytoplankton" component (PC_{IV}) and explained only 10.1% of the variance (Table 1). Concentrations of SRP were so low so as to be undetectable in many instances (Fig. 6). The relationship between SRP and Chl a was very weak and may have been influenced by other factors yet determined.

Figure Legends

Fig. 1. Map of original sampling stations in Biscayne Bay showing zones of similar influence (ZSI) from cluster analysis of mean and SD of five principal component scores. The ZSI are: Alongshore (●), Inshore (+), Main Bay (▲), Card Sound (◆), Ocean Channel (■), and Turkey Point (□). Note that the Fowey Rocks station has been incorporated into our Florida Keys National Marine Sanctuary water quality monitoring program.

Fig. 2. Map of modified sampling stations in Biscayne Bay showing zones of similar influence (ZSI) from cluster analysis of mean and SD of five principal component scores. The ZSI are: Alongshore (●), Inshore (+), Main Bay (▲), Card Sound (◆), and North Bay (■).

Fig. 3. Box-and whisker plots of PC_I factors: NO_2 (μM), NO_3 (μM), NH_4 (μM), salinity (ppt), and total phosphorus (μM) by zone. The center horizontal line in the box is the median, 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 is the 95 % confidence interval of the median. When notches between boxes do not overlap, the medians are significantly different. Outliers have not been included so as to increase resolution of plot.

Fig. 4. Box-and-whisker plots of PC_{II} factors: total organic nitrogen (TON; μM), alkaline phosphatase activity (APA; $\mu M\ h^{-1}$), and total organic carbon (TOC; μM) as in Fig. 2.

Fig. 5. Box-and-whisker plots of PC_{III} factors: dissolved oxygen (DO; $mg\ l^{-1}$), and temperature ($^{\circ}C$) as in Fig. 2.

Fig. 6. Box-and-whisker plots of PC_{IV} factors: soluble reactive phosphorus (SRP; μM), chlorophyll *a* (Chl *a*; $\mu g\ l^{-1}$) and plot of PC_V factor: turbidity (NTU) as in Fig. 2.

Table 1. Results of principal component analysis are shown as factor loadings (correlations between the raw variables and the principal components) for the first five principal components after VARIMAX rotation. For clarity, loadings with a magnitude >0.50 are shown in boldface type.

Parameter	Principal Component				
	PC _I	PC _{II}	PC _{III}	PC _{IV}	PC _V
NO ₂	0.91	0.04	0.02	0.08	0.06
NO ₃	0.85	0.07	-0.05	-0.12	0.05
NH ₄	0.72	0.01	0.21	0.27	-0.06
Salinity	-0.70	-0.43	0.27	0.24	-0.11
TP	0.52	0.30	0.03	0.12	-0.31
TON	0.30	0.76	0.07	-0.17	0.10
APA	0.22	0.72	-0.08	0.22	0.22
TOC	-0.10	0.55	0.00	0.12	-0.34
DO	0.09	0.23	-0.88	-0.11	0.00
Temperature	0.12	0.22	0.86	-0.12	0.12
Chl <i>a</i>	-0.05	0.11	0.04	0.88	-0.02
SRP	0.42	-0.03	-0.07	0.50	0.15
Turbidity	0.01	-0.09	-0.10	-0.09	-0.85
%Total Variation	24.3	13.9	12.7	10.1	8.1

Cumulative Variance Explained = 69.1 %

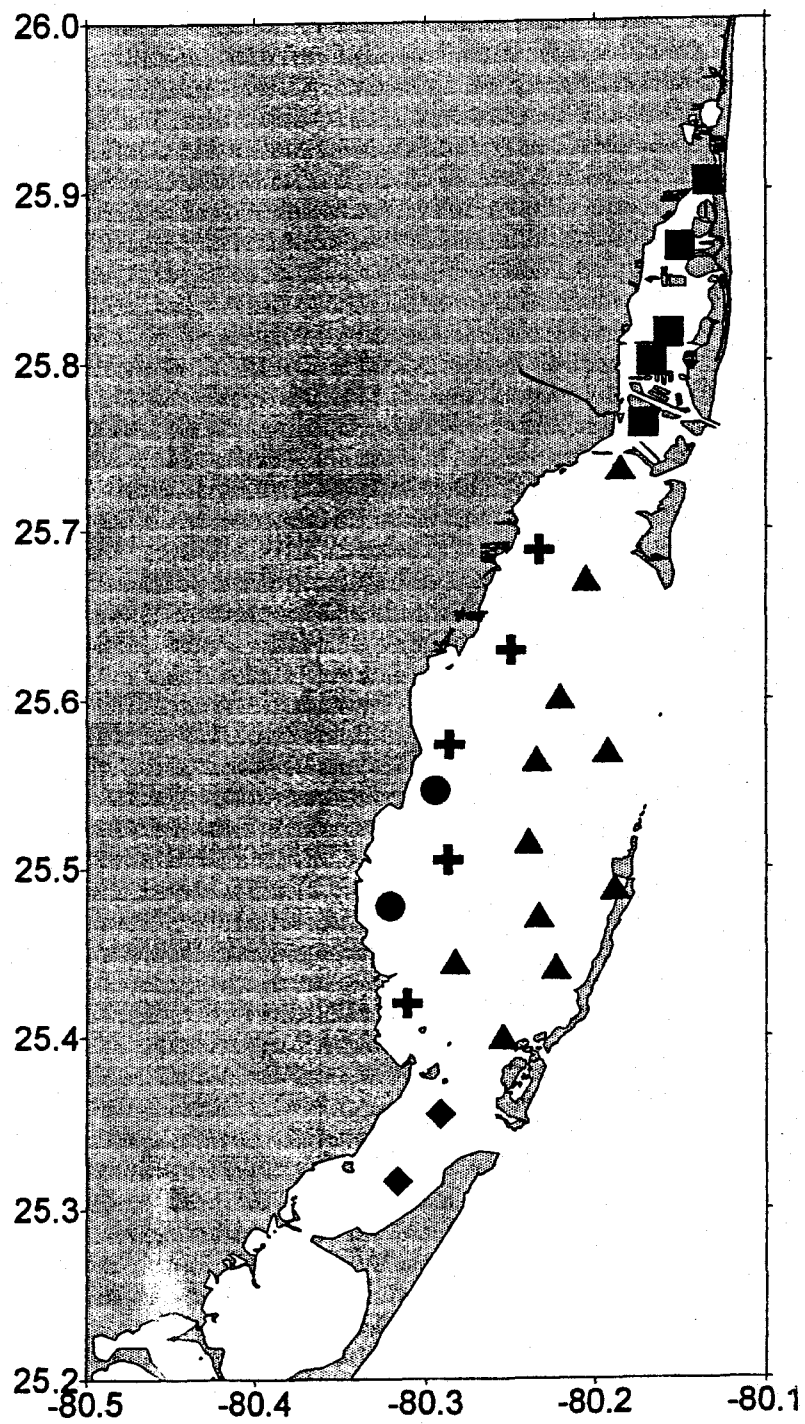


Figure 2

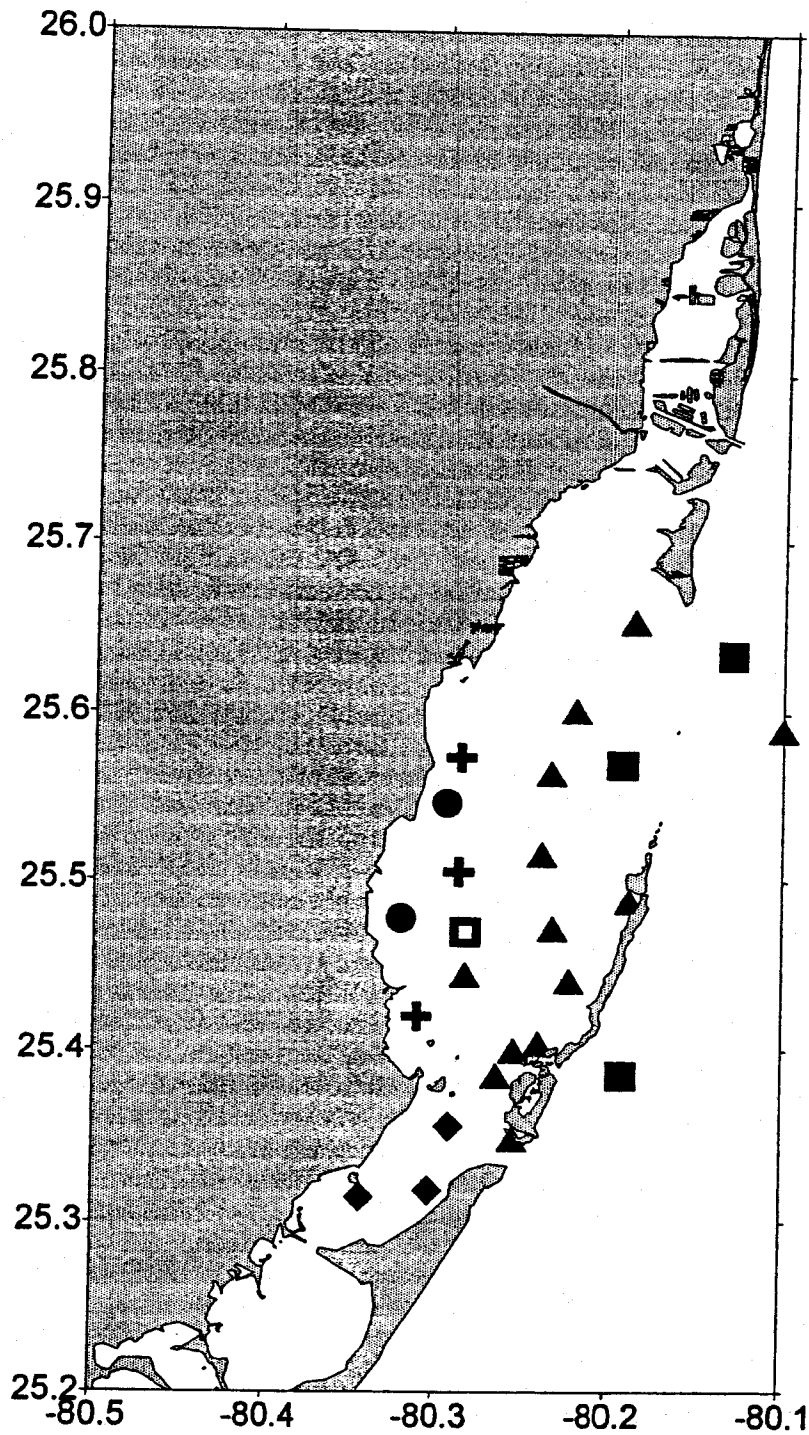


Figure 1

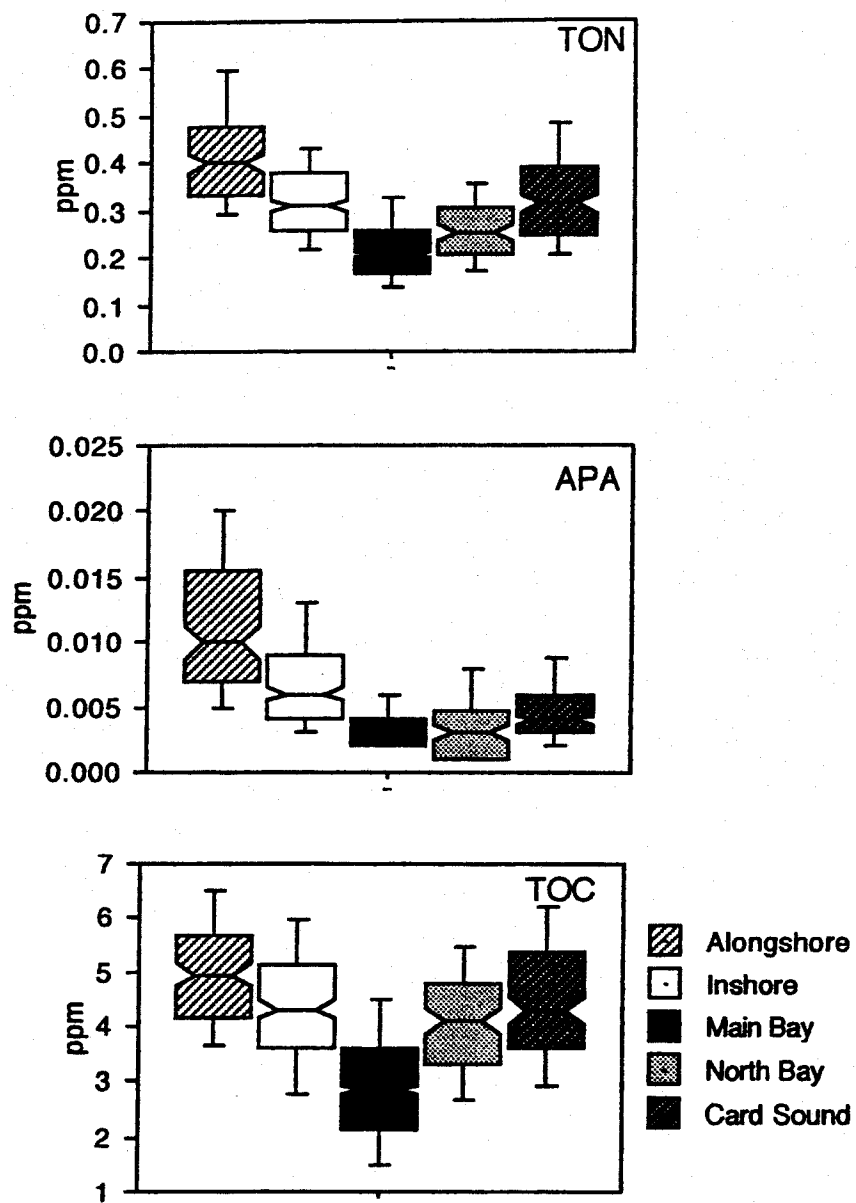


Figure 4

40 ppb

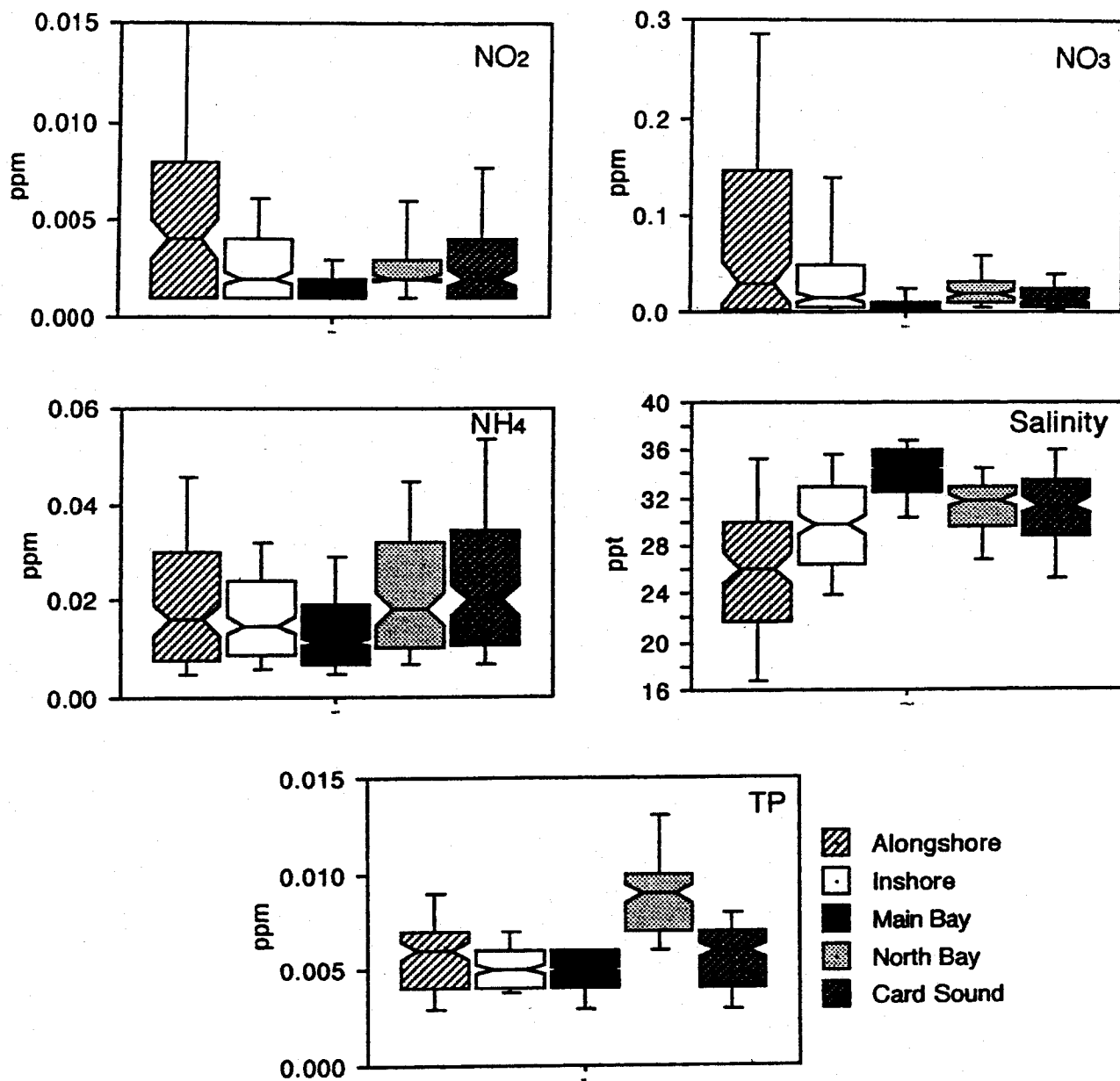


Figure 3

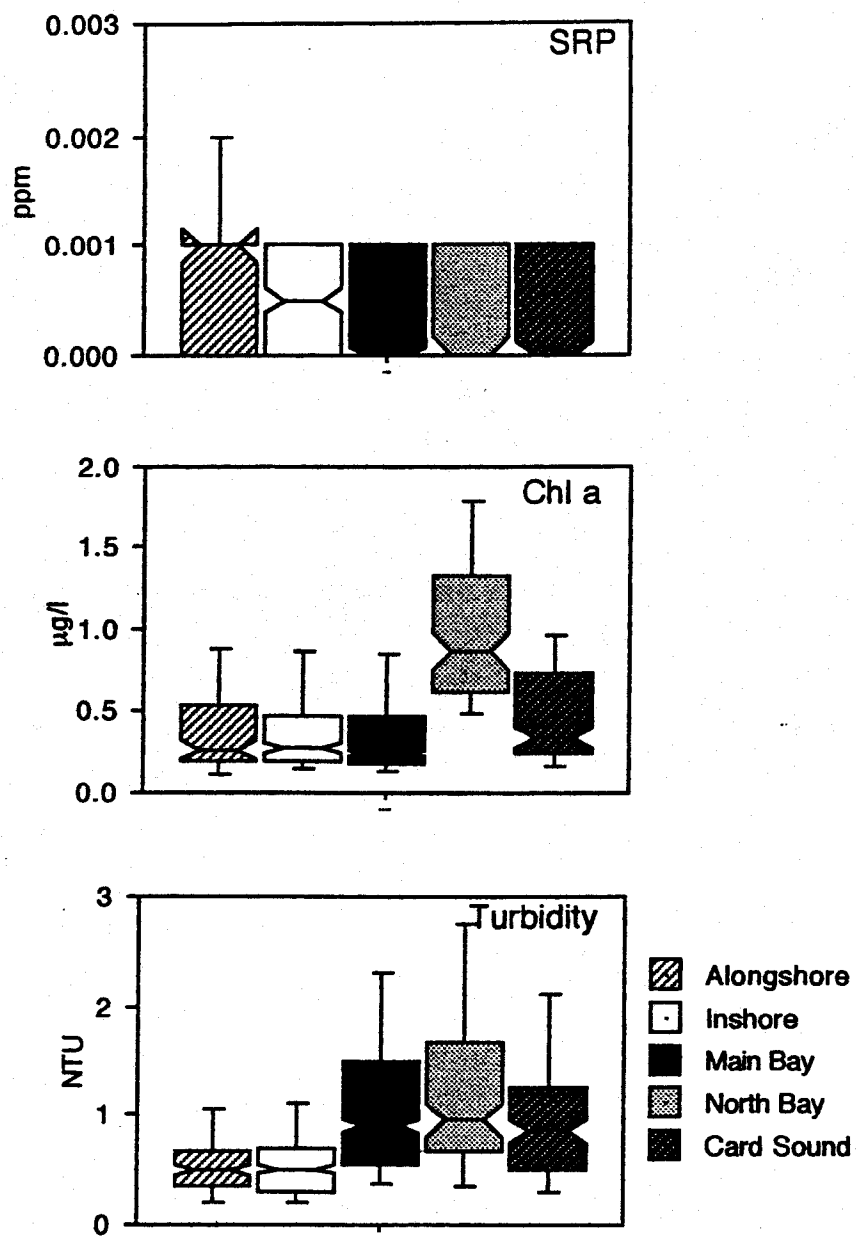


Figure 6

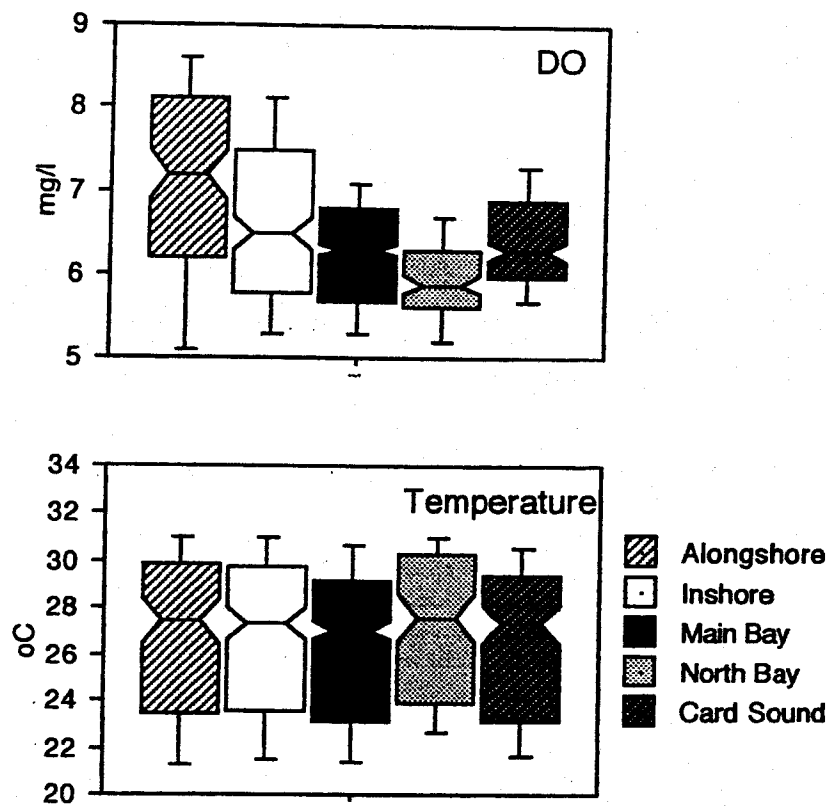


Figure 5

SOUTHWEST FLORIDA SHORE MAP

Charting and Geodetic services with additional data from the Defense Mapping Agency, Geological Survey, Corps of Engineers, and British Admiralty Charts.

GULF STREAM CURRENTS

From investigation by the Coast and Geodetic Survey in 1885, 1886 and 1887.

The direction and velocity of the current are indicated at each station by arrows; the long arrow indicates maximum and the short arrow minimum velocity figures show knots.

LOCALITY OF CURRENT STATIONS

East of Farway Rocks (5 stations)
South of Rebecca Shoal (5 stations)

TIME OF MAX. VELOCITY BEFORE MOONS TRANSIT

9 h 00 m
9 h 20 m

NOTE A

Navigation regulations are published in Chapter 2, U.S. Coast Pilots 4 & 5, or weekly Notice to Mariners which include new or revised regulations. Information concerning the regulations may be obtained at the Office of the District Engineer, Corps of Engineers, in Jacksonville, Florida.

Anchorage regulations may be obtained at the Office of the Commander, 7th Coast Guard District in Miami, Florida.

Refer to section numbers shown with area designation.

CAUTION

Temporary changes or defects in aids to navigation are not indicated on this chart. See Notice to Mariners.

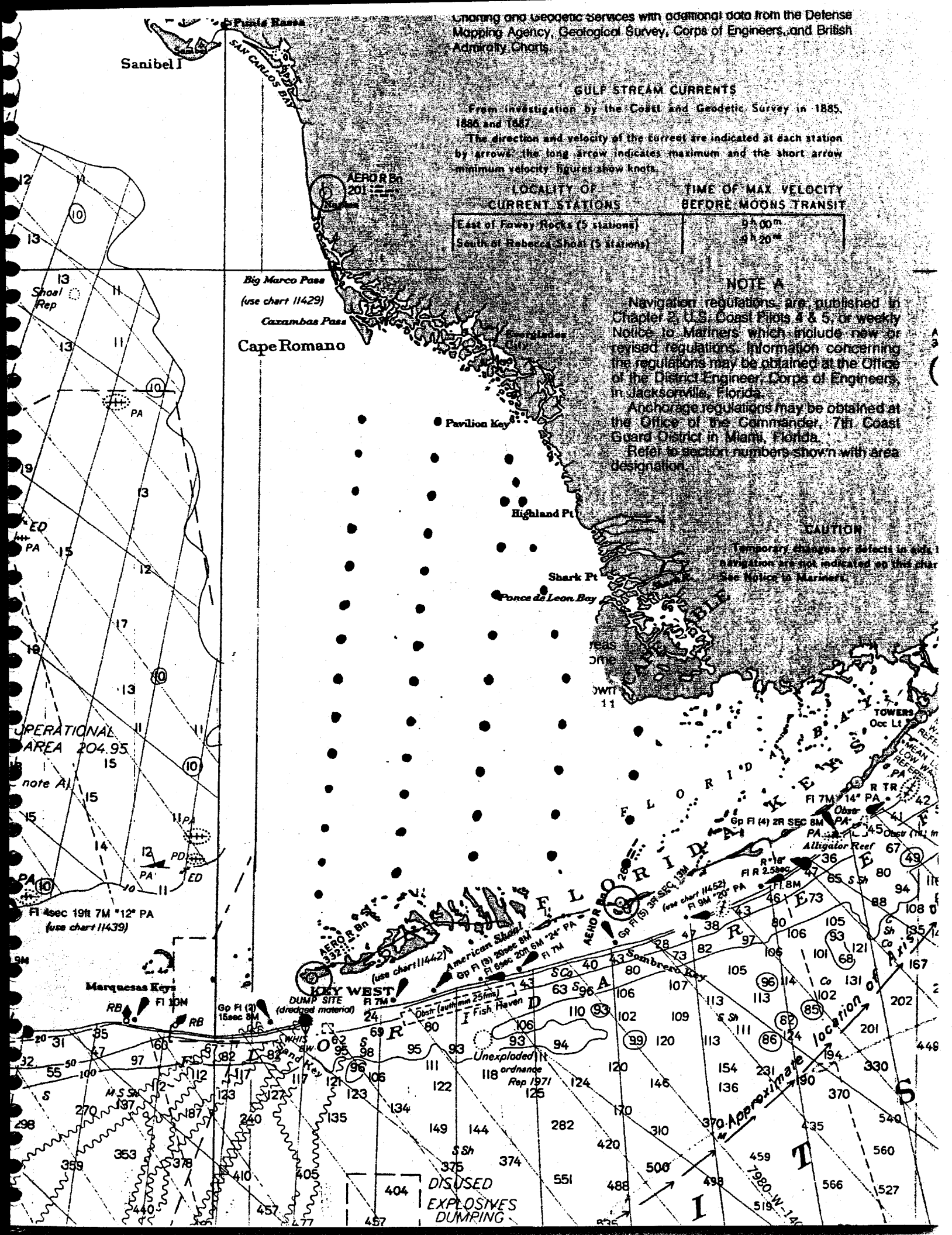


Table 1: Southwest Florida Shelf Station Summary

Station Number	Latitude	Longitude	Period of Record	Surveys
351	24 41.50	81 47.50	May 95 - Oct 97	1-10
352	24 46.55	81 46.98	May 95 - Oct 97	1-10
353	24 51.50	81 46.60	May 95 - Oct 97	1-10
354	24 56.48	81 46.12	May 95 - Oct 97	1-10
355	25 01.48	81 45.75	May 95 - Oct 97	1-10
356	25 06.46	81 45.23	May 95 - Oct 97	1-10
357	25 11.47	81 44.72	May 95 - Oct 97	1-10
358	25 16.48	81 44.29	May 95 - Oct 97	1-10
359	25 21.50	81 43.80	May 95 - Oct 97	1-10
360	25 26.47	81 43.26	May 95 - Oct 97	1-10
361	25 31.48	81 42.90	May 95 - Oct 97	1-10
362	25 36.52	81 42.40	May 95 - Oct 97	1-10
363	25 41.52	81 41.90	May 95 - Oct 97	1-10
364	25 41.50	81 32.00	May 95 - Oct 97	1-10
365	25 36.51	81 32.36	May 95 - Oct 97	1-10
366	25 31.56	81 32.93	May 95 - Oct 97	1-10
367	25 26.55	81 33.30	May 95 - Oct 97	1-10
368	25 21.51	81 33.80	May 95 - Oct 97	1-10
369	25 16.53	81 34.32	May 95 - Oct 97	1-10
370	25 11.51	81 34.75	May 95 - Oct 97	1-10
371	25 06.50	81 35.21	May 95 - Oct 97	1-10
372	25 01.50	81 35.72	May 95 - Oct 97	1-10
373	24 56.53	81 36.18	May 95 - Oct 97	1-10
374	24 51.53	81 36.65	May 95 - Oct 97	1-10
375	24 46.54	81 37.07	May 95 - Oct 97	1-10
376	24 50.60	81 26.30	May 95 - Oct 97	1-10
377	24 56.10	81 25.90	May 95 - Oct 97	1-10
378	25 01.00	81 24.95	May 95 - Oct 97	1-10
379	25 06.00	81 24.53	May 95 - Oct 97	1-10
380	25 11.00	81 24.00	May 95 - Oct 97	1-10
381	25 16.00	81 23.70	May 95 - Oct 97	1-10
382	25 21.00	81 23.20	May 95 - Oct 97	1-10
383	25 25.95	81 22.67	May 95 - Oct 97	1-10
384	25 30.93	81 22.20	May 95 - Oct 97	1-10
385	25 36.01	81 21.79	May 95 - Oct 97	1-10
386	25 33.33	81 20.43	May 95 - Oct 97	1-10
387	25 30.53	81 19.01	May 95 - Oct 97	1-10
388	25 25.50	81 17.82	May 95 - Oct 97	1-10
389	25 20.50	81 16.62	May 95 - Oct 97	1-10
390	25 15.60	81 15.61	May 95 - Oct 97	1-10
391	25 10.50	81 14.32	May 95 - Oct 97	1-10
392	25 05.50	81 14.90	May 95 - Oct 97	1-10
393	25 00.50	81 15.20	May 95 - Oct 97	1-10
394	24 55.50	81 15.60	May 95 - Oct 97	1-10
395	24 52.70	81 11.50	May 95 - Oct 97	1-10
396	24 50.00	81 07.70	May 95 - Oct 97	1-10
397	24 55.00	81 07.10	May 95 - Oct 97	1-10
398	25 00.00	81 06.60	May 95 - Oct 97	1-10
399	25 05.00	81 05.96	May 95 - Oct 97	1-10

SOUTHWEST FLORIDA SHELF: Preliminary Spatial Analysis

This section presents a preliminary analysis and will be repeated as more years of data are collected.

STATISTICAL ANALYSES

In order to assess the underlying patterns in the distribution of the measured parameters, we followed the procedure of Boyer et al. (1997). Briefly, principal component analysis (PCA) was used to extract 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 over the period of record (POR) for each station were then used as independent variables in a cluster analysis in order to aggregate stations into zones of similar influence (ZSI). The purpose of this analysis was to collapse the number of stations into a few groups which could then be analyzed in more detail.

Once stations were grouped by cluster analysis, statistical analysis of the water chemistry among ZSI was possible (see box-and-whiskers plots, Figs. 2-5). 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. The box-and-whisker plot is a powerful statistic as it shows the median, range, distribution of the data as well as serving as a graphical, nonparametric ANOVA. In addition, differences in parameters among ZSI were quantified using Kruskal-Wallis test with significance set at $P < 0.05$.

RESULTS

RANGES AND MEDIANS OF DATA

Large ranges in most measured parameters were the norm owing to the wide spatial and temporal sampling plan (Table 1). Medians are reported as the nonparametric statistic of central tendency due to the skewed nature of most water chemistry data. Overall, the Southwest Florida Shelf was warm (median temperature of 27.7°C) with normal seawater salinity (35.3 ppt). The median DO was 6.3 mg l⁻¹, or 95% of saturation. DIN concentrations were a very small fraction of the TN pool (2.6%) with TON making up the bulk. NH₄ was the dominant DIN species in almost all of the samples (83% of DIN). SRP concentrations were low (0.001 ppm) and comprised 9% of the TP pool (0.011 ppm). Chl *a* concentrations were also generally low (0.8 µg l⁻¹) but ranged from 0.1 to 7.1 µg l⁻¹. The TN:TP ratio ranged from 15-140 with the median of 47 suggesting a strong and consistent P limitation of the water column.

PRINCIPAL COMPONENT ANALYSIS

PCA identified five composite variables (hereafter called PC_I , PC_{II} , 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 1), indicate five separate modes of variation in the data. PC_I had high factor loadings for NO_3 and NO_2 and was called the " NO_x " component. PC_{II} was composed of NH_4 , SRP, and TON (marginally) and called the "Recycled" component. The "Phytoplankton" (PC_{III}) included TP, Chl a , and turbidity and explained 16% of the total variance. The PC_{IV} group included APA, TOC, and temperature. Finally, SiO_2 and salinity were inversely related in PC_V , denoting a freshwater source of SiO_2 to the Shelf from the Shark River Slough. These five principal components accounted for 70.6 % of the total variance of the original variables.

CLUSTER ANALYSIS

A k-means clustering algorithm, using the mean and SD of the five factor scores of each station, objectively classified the 49 sampling sites into 3 groups having similar water quality, or zones of similar influence (ZSI, Fig. 1). The first cluster was composed of 2 stations closest to the shore off Cape Sable; they were called the "Sable" group. The second cluster was made up of the 7 more northerly stations nearest the coast and called "Shark" after the Shark Slough, the main source of freshwater to the region. The remaining stations were called the "Shelf" group.

WATER QUALITY CHARACTERISTICS AMONG ZSI

The nutrient parameters composing PC_I and PC_{II} explained 27.6% of the variance (Table 1). It is clear that the Sable stations have much higher concentrations of NO_3 , NO_2 , NH_4 , and SRP (Fig. 2) while the Shark and Shelf stations were similar. In addition, PC_{III} shows that there is a decreasing concentration gradient from Sable-Shark-Shelf for TP, Chl a and turbidity (Fig. 3). The pattern in Figure 4 is that Sable > Shelf > Shark for APA, TOC and temperature. Finally, the inverse relationship between salinity and SiO_2 is evident for all ZSI (Fig. 5). Although these analyses are very preliminary (only 10 sampling events) it is possible to speculate that the clusters are formed as a function of hydrology and circulation patterns. We believe that the Sable stations clearly show the input of freshwater from Shark Slough being transported south and east around the Cape. Water overlying the Shark stations probably originates somewhere north of the Ten Thousand Islands. Our level of resolution is very low due to the limited numbers of sampling events and by the relatively large spatial gap between coastal and Shelf sampling sites. A better understanding of local circulation patterns in addition to increased density and frequency of sampling in the nearshore region may help define the coupling between freshwater inflow and Shelf water quality.

Table 1. Results of principal component analysis are shown as factor loadings (correlations between the raw variables and the principal components) for the first five principal components after VARIMAX rotation. For clarity, loadings with a magnitude >0.50 are shown in boldface type.

Parameter	Principal Component				
	PC _I	PC _{II}	PC _{III}	PC _{IV}	PC _V
NO ₃	0.822	-0.058	0.172	0.097	0.279
NO ₂	0.891	0.194	0.029	-0.027	-0.025
NH ₄	0.306	0.744	0.027	0.217	0.006
TON	0.037	0.482	0.234	0.283	0.406
TP	-0.026	0.358	0.731	0.095	0.127
SRP	-0.071	0.848	0.033	-0.104	0.080
APA	-0.111	0.152	0.230	0.620	-0.108
Chl <u>a</u>	0.190	-0.121	0.750	0.058	0.048
TOC	0.146	-0.108	0.170	0.740	0.425
SiO ₂	0.426	0.279	0.047	0.080	0.712
Salinity	-0.014	0.033	-0.069	0.130	-0.852
Temperature	0.096	0.081	-0.349	0.809	-0.114
DO	-0.144	-0.440	0.331	-0.430	0.268
Turbidity	0.048	0.008	0.882	-0.084	0.043
%Total Variation	13.24	14.31	16.30	14.03	12.72

Cumulative Variance Explained = 70.6 %

Figure Legends

Fig 1. Map of sampling stations of the Southwest Florida Shelf showing zones of similar influence (ZSI) from cluster analysis of mean and SD of five principal component scores. The ZSI are: Cape Sable (●), Shark Slough (■), and Shelf (+).

Fig. 2. Box-and whisker plots of PC_I factors: NO_3 (ppm), NO_2 (ppm) and PC_{II} factors: NH_4 (ppm), and SRP (ppm) by zone. The center horizontal line in the box is the median, 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 is the 95% confidence interval of the median. When notches between boxes do not overlap, the medians are significantly different. Outliers have not been included so as to increase resolution of plot.

Fig. 3. Box-and-whisker plots of PC_{III} factors: TP (ppm), chlorophyll a ($\mu g\ l^{-1}$), and turbidity (NTU) as in Fig. 2.

Fig. 4. Box-and-whisker plots of PC_{IV} factors: APA ($\mu M\ h^{-1}$), TOC (ppm), and temperature ($^{\circ}C$) as in Fig. 2.

Fig. 5. Box-and-whisker plots of PC_V factors: SiO_2 (ppm) and salinity (ppt) as in Fig. 2.

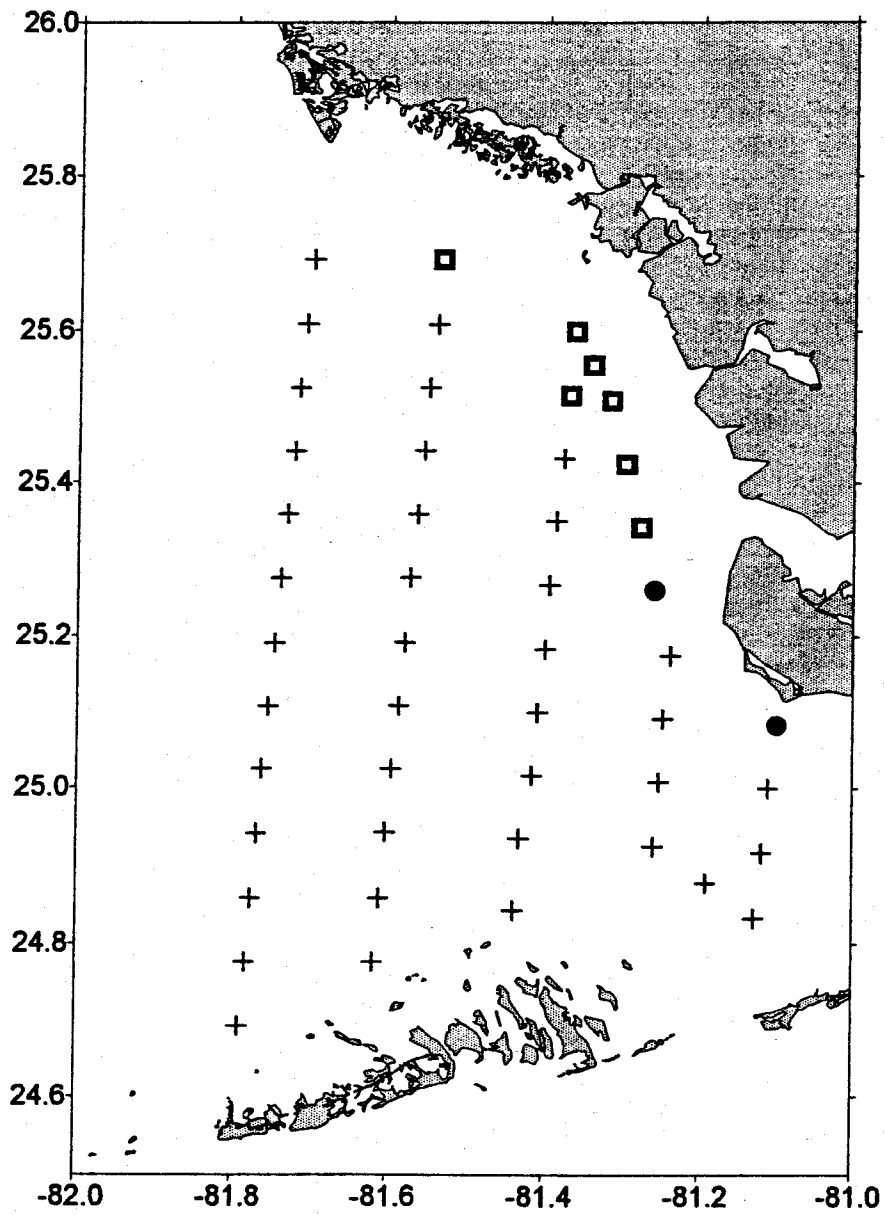


Figure 1

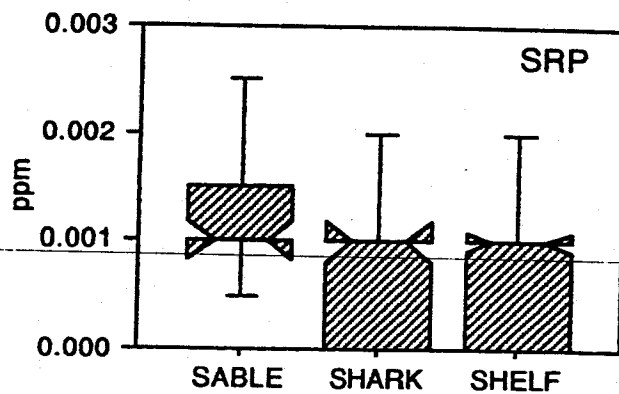
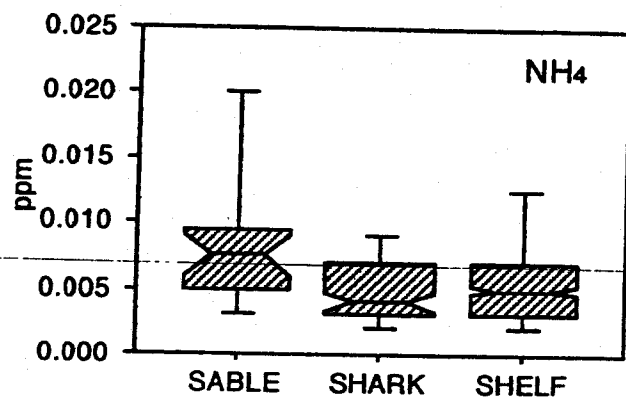
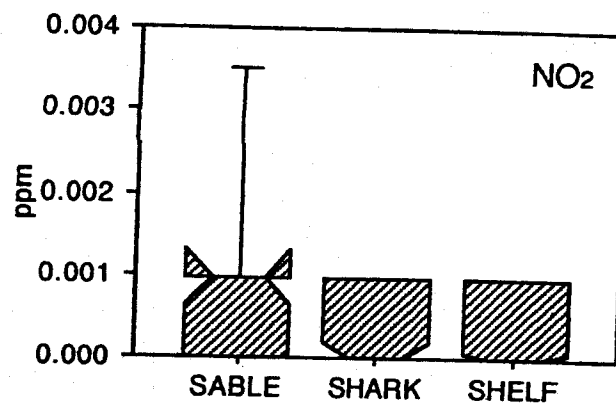
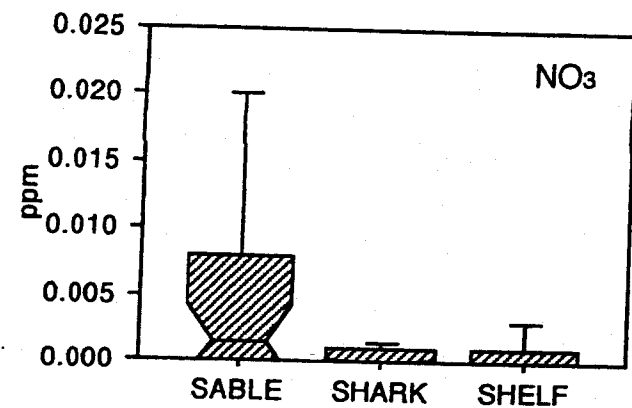


Figure 2

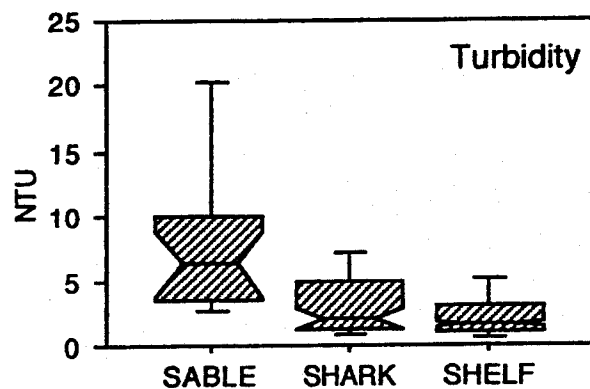
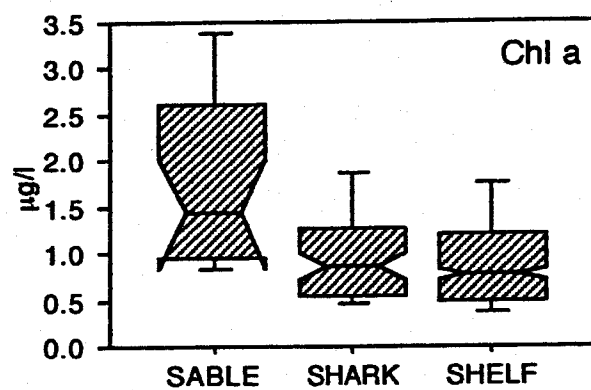
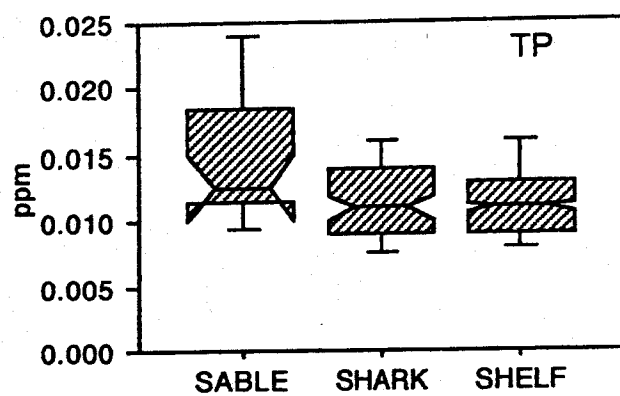


Figure 3

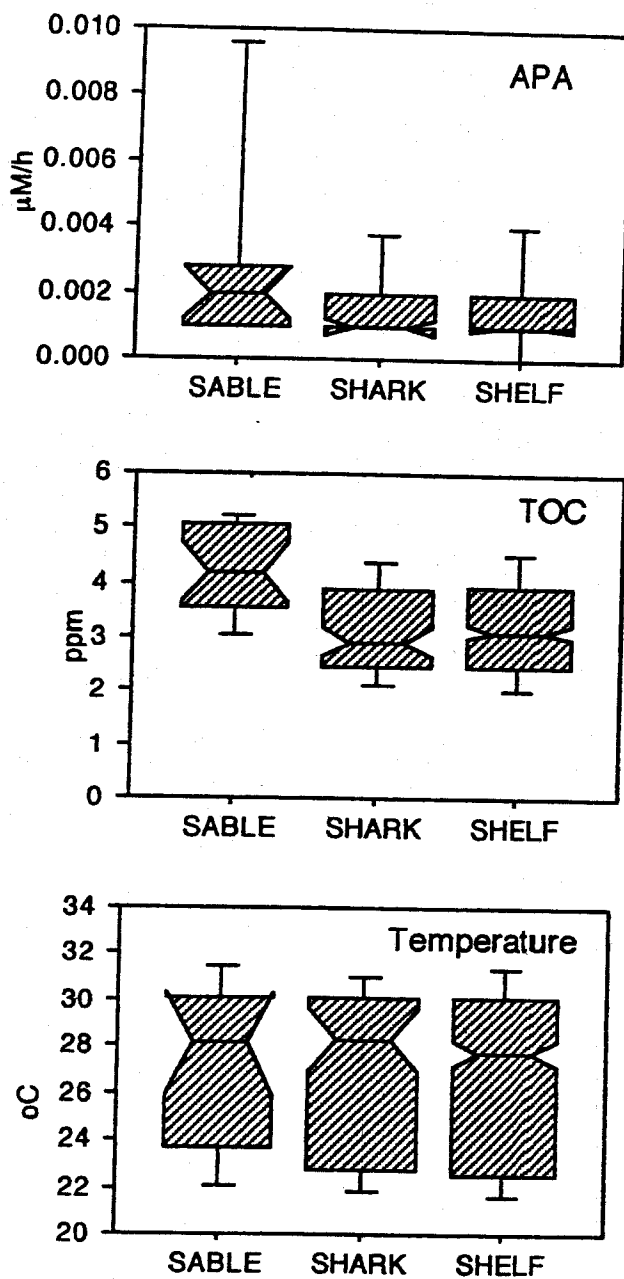


Figure 4

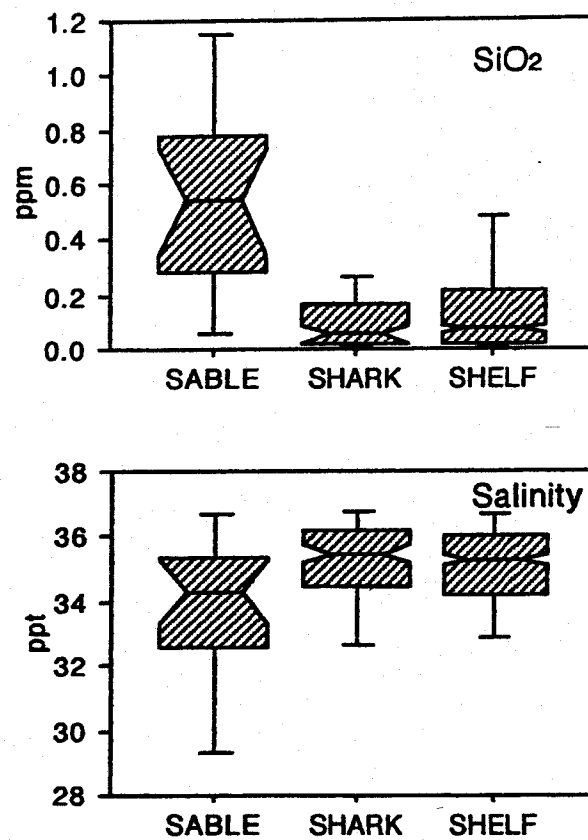


Figure 5

