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

JOSEPH N. BOYER[1]
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 (PCII) contained NO_2^-, NO_3^-, and NH_4^+, 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 NH_4^+ concentrations but very low NO_3^-, 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 embayments (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 Narragansett 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

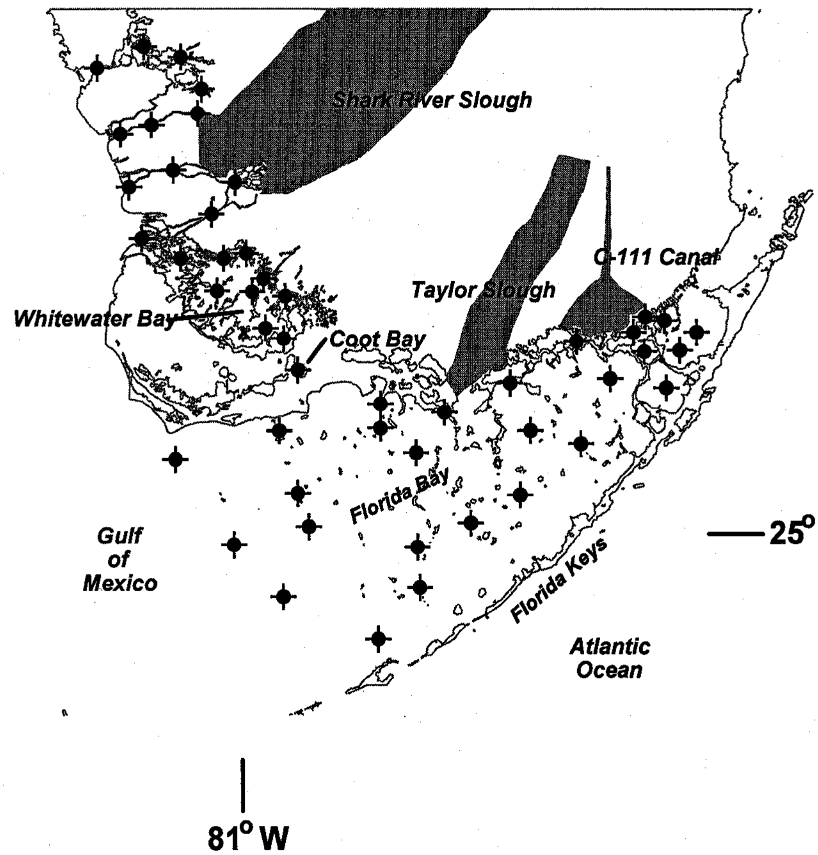

Fig 1. Map of Florida Bay and Whitewater Bay showing the sampling stations.

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 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 (μM 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 (μg 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 $NO_x^- - NO_2^-$. Total inorganic nitrogen (TIN) was calculated as $NO_x^- + NH_4^+$. Total organic nitrogen (TON) was defined as TN-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 component 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, nonparametric ANOVA. In addition, differences in parameters among ZSI were quantified using Kruskall-Wallace 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 μM) and composed only 8% of the TP pool. Chl *a* concentrations were low overall, 1.3 μg l^{-1}, and ranged from 0.02 to 17.8 μg 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_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),

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 *a* (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 NO_2^-, NO_3^-, and NH_4^+ 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_{IV}) 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

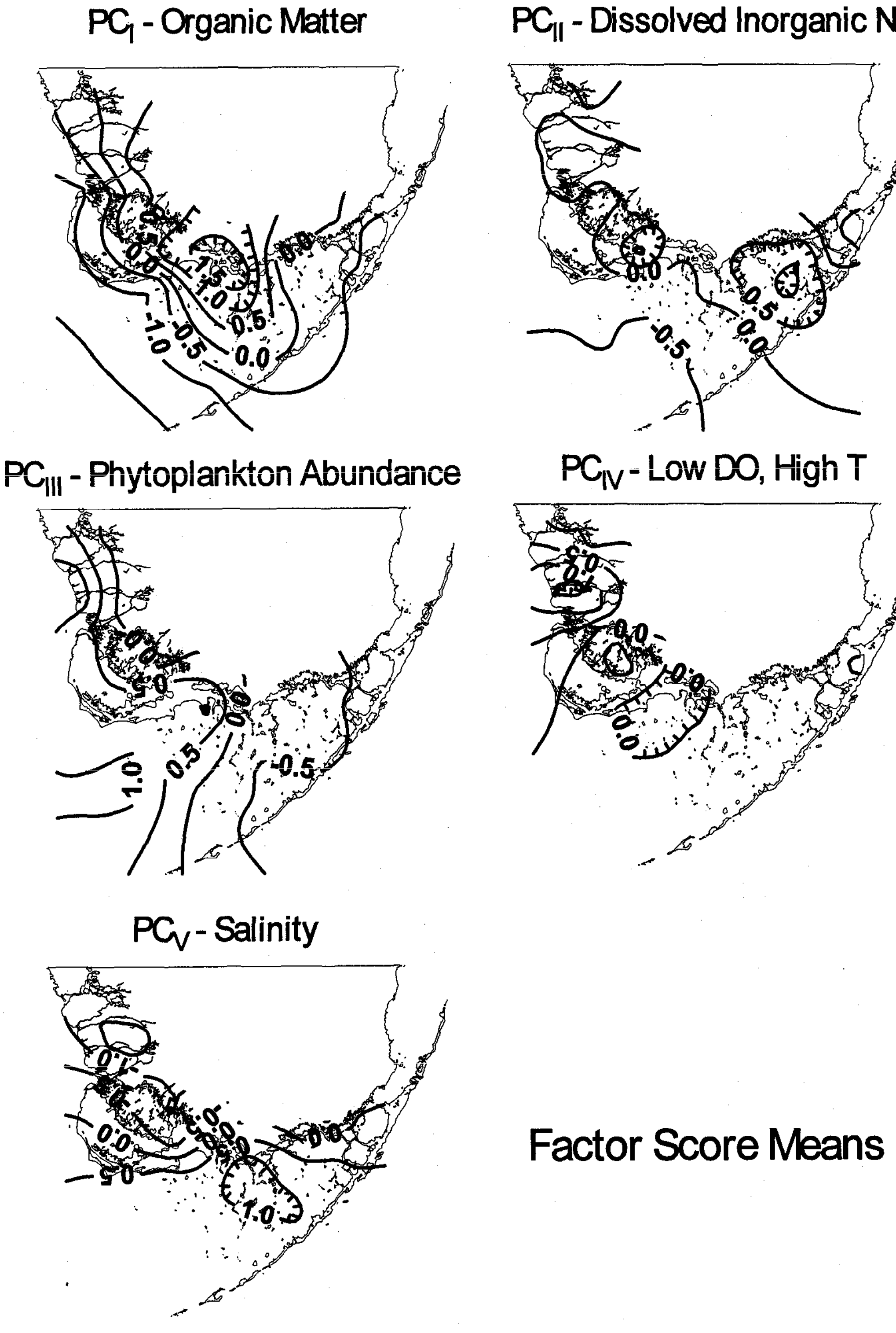

Fig 2. Set of maps, showing the spatial distributions of the mean factor scores for the five retained principal components. Hatchures point toward higher values.

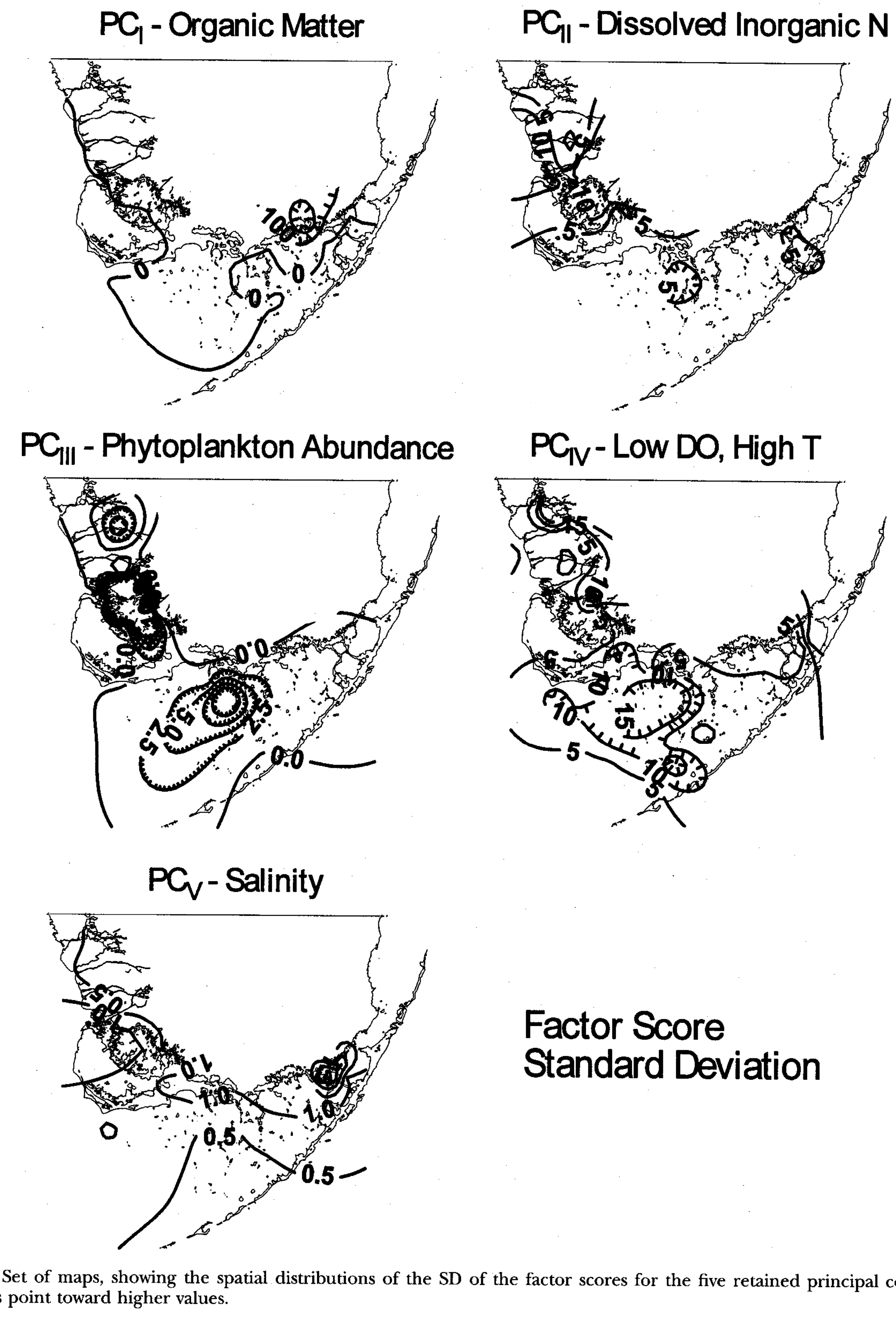

Fig 3. Set of maps, showing the spatial distributions of the SD of the factor scores for the five retained principal components. Hatchures point toward higher values.

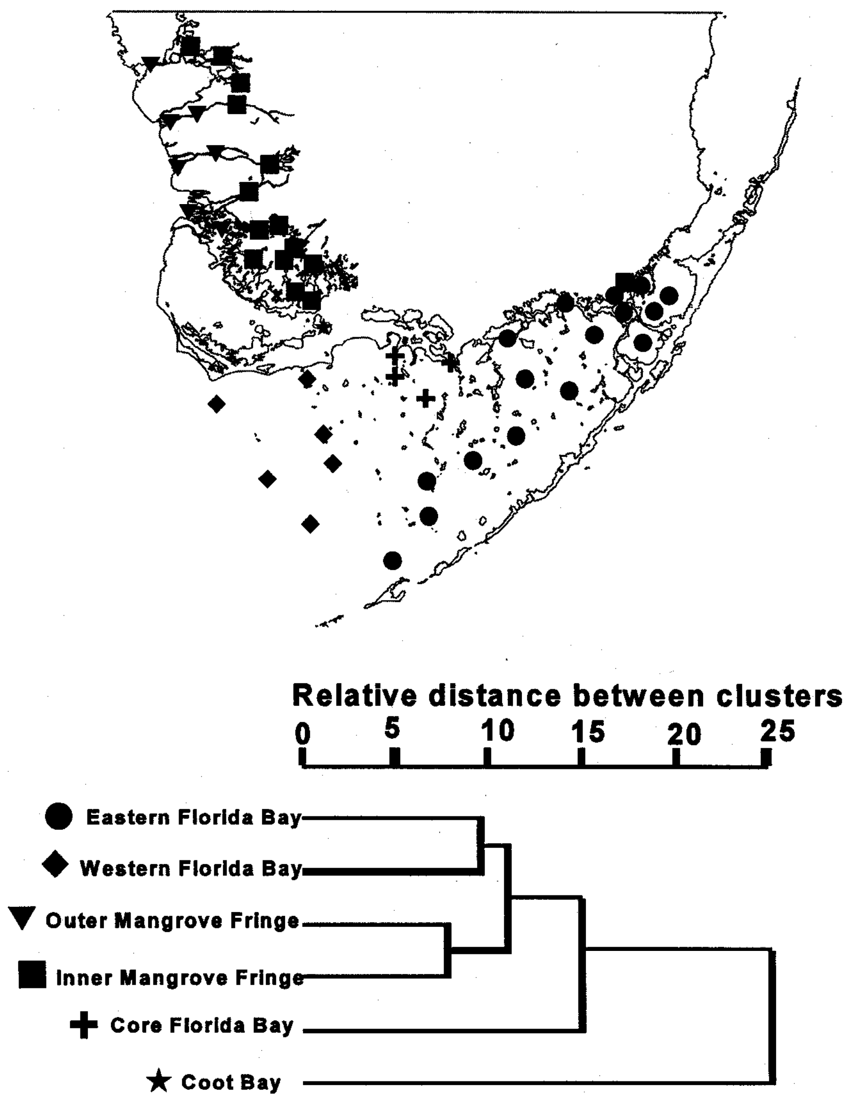

Fig 4. Map and cladogram of zones of similar influence (ZSI) as a result of cluster analysis of mean and SD of five retained principal component scores.

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 μM 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 μM) greater than Eastern Bay (713 μM); these in turn, were greater than the Western Bay (419 μM). In the Whitewater Bay area, Coot Bay had the highest median TOC overall (2013 μM; $p = 0.01$ and 0.01), with lower concentrations in the Inner Mangrove and Outer Mangrove zones (1355 μM and 1147 μM; $p = 0.03$).

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 μM; 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 *a*	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). NO_2^- 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 NO_3^- 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). NO_3^- 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). NH_4^+ 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

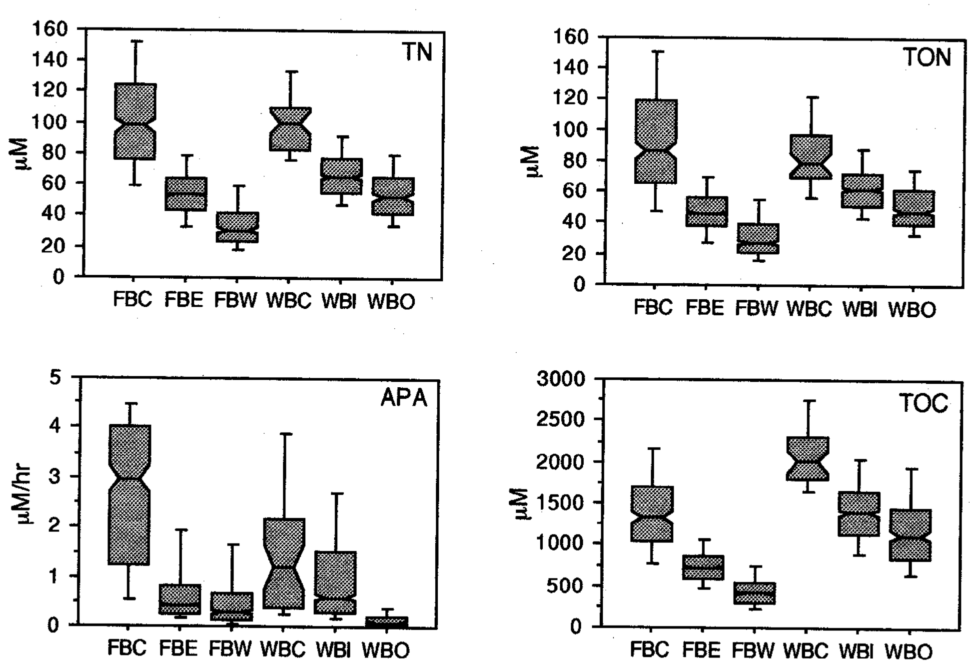

Fig 5. Box-and-whisker plots of PC_I factors: TN (μM), TON (μM), APA (μM h^{-1}), and TOC (μM). The center horizontal line in the box is the median, the top and bottom of the box are the 25th and 75th percentiles (quartiles), and the ends of the whiskers are the 5th and 95th percentiles. The notch is 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.

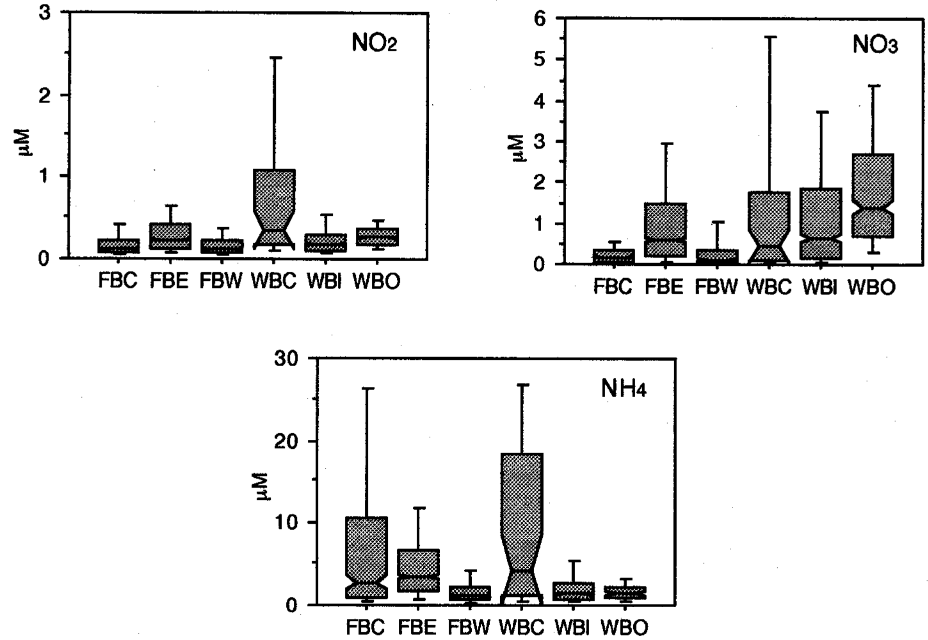

Fig 6. Box-and whisker plots of PC_{II} factors: NO_2^- (μM), NO_3^- (μM), and NH_4^+ (μM).

comparable NH_4^+ 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

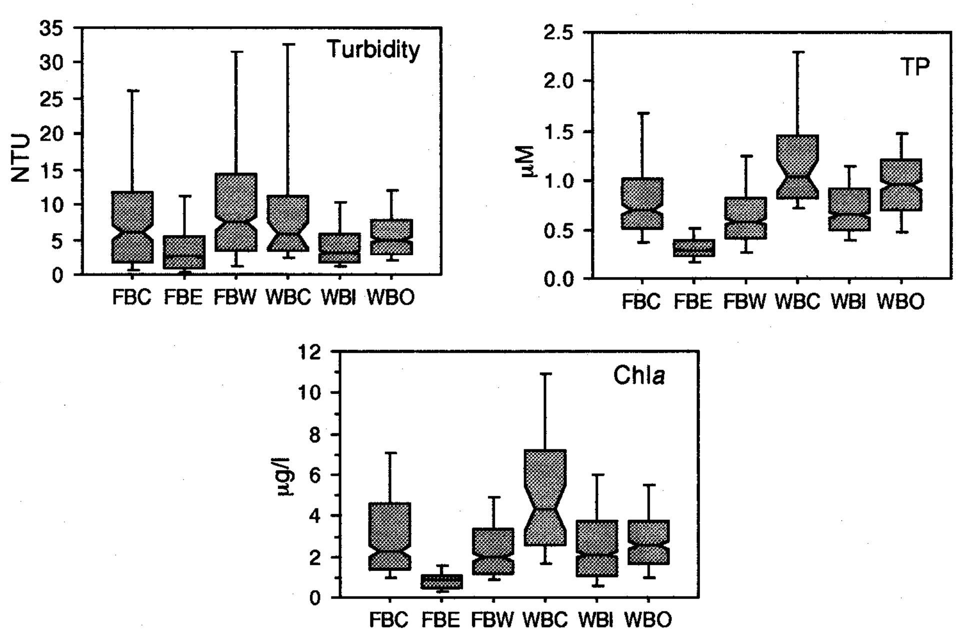

Fig 7. Box-and-whisker plots of PC_{III} factors: turbidity (NTU), TP (μM), and Chl *a* (μg l^{-1}).

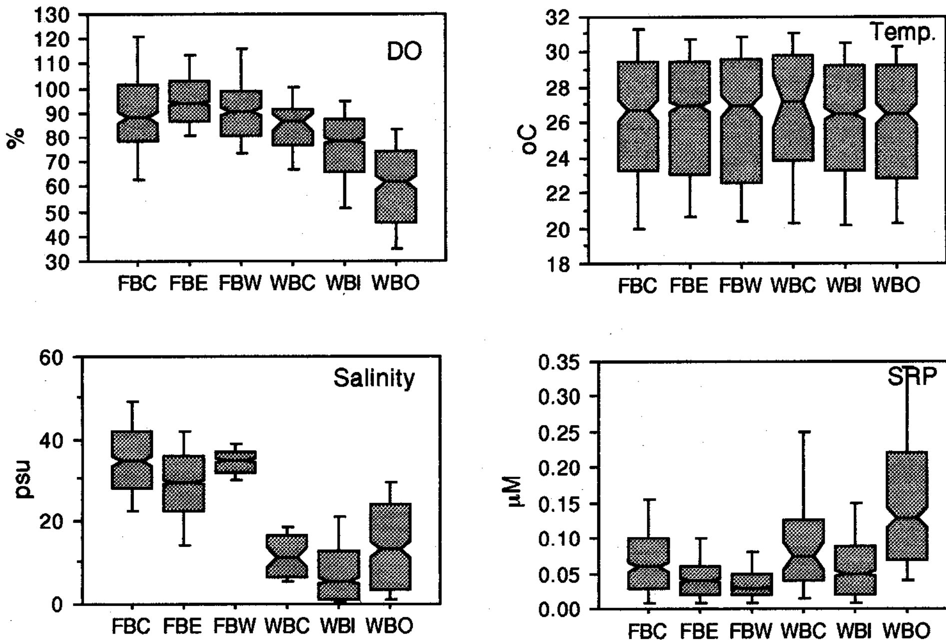

Fig 8. Box-and-whisker plots of PC_{IV} and PC_V factors: DO saturation (%), temperature (°C), and salinity (‰). SRP (µM) was not a factor in the PCA results.

than the Inner Mangrove (0.63 µM). Chl *a* concentrations in the Eastern Bay (0.90 µg l^{-1}) were significantly lower than both Western and Core bays (1.98 µg l^{-1} and 2.28 µg l^{-1}; Fig. 7). Median Chl *a* at the Coot Bay station (4.34 µg l^{-1}) was significantly greater than both Inner Mangrove and Outer Mangrove zones (2.00 µg l^{-1} and 2.31 µg l^{-1}), and had a maximum concentration of 17.78 µg 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 runoff 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 µM. SRP was much higher in the Outer Mangrove (0.14 µM) than the Inner Mangrove zone (0.05 µM; $p = 0.01$).

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-

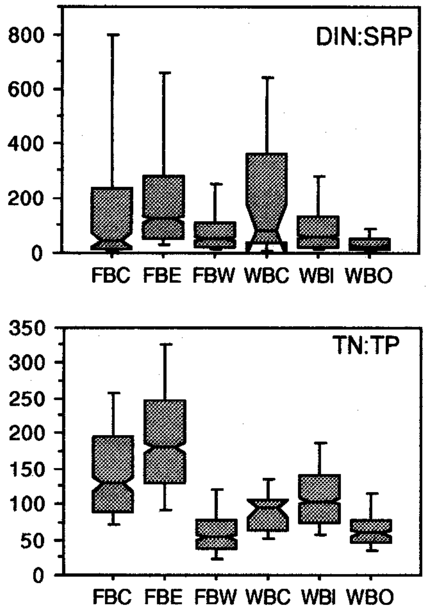

Fig 9. Box-and whisker plots of molar ratios of TIN:SRP and TN:TP.

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 μM), 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 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 μg 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 (Phlips 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 $\mu M\ h^{-1}$), 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 morphology 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.

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