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Biogeochemical classification of South Florida's estuarine and coastal waters

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ABSTRACT

South Florida's watersheds have endured a century of urban and agricultural development and disruption of their hydrology. Spatial characterization of South Florida's estuarine and coastal waters is important to Everglades' restoration programs. We applied Factor Analysis and Hierarchical Clustering of water quality data in tandem to characterize and spatially subdivide South Florida's coastal and estuarine waters. Segmentation rendered forty-four biogeochemically distinct water bodies whose spatial distribution is closely linked to geomorphology, circulation, benthic community pattern, and to water management. This segmentation has been adopted with minor changes by federal and state environmental agencies to derive numeric nutrient criteria.

1. Introduction

Most decisions on coastal and marine resource management require habitat classification systems which adequately convey the concept of homogeneity of spatial clusters, in turn adapted to the objectives of such managerial decision. Estuarine and coastal zones have been classified around the world using diverse approaches and criteria including salinity structure, geomorphology, water circulation, etc. (Digby et al., 1998; Spalding et al., 2007). These classification schemes become critical as the need for resource management tools increases to face consequences of development in the coastal zones, especially in regions like South Florida, where estuaries and coasts have experienced the environmental impact of anthropogenic interventions since the 1900s, including major disruptions of its hydrology, sustained urban and agricultural development and climate change (Nuttle et al., 2000; Sklar et al., 2001; Briceño and Boyer, 2010).

The US-Environmental Protection Agency (EPA) and the Florida Department of Environmental Protection (FDEP) are in the process of deriving numeric nutrient criteria for South Florida's coastal and estuarine waters. Given that spatial–temporal characterization of these water bodies is necessary for such derivation, and important to Everglades' protection and restoration programs, the National Park Service and Florida International University joined resources to obtain a biogeochemical and statistically robust subdivision of these water bodies. We started with *a priori* sub-division of South Florida into basins (e.g., Biscayne Bay, Florida Bay, Florida Keys, Gulf Shelf, Ten-Thousand Islands and Pine Island-Rookery Bay) that reflected reported differences in geomorphology (Davis et al., 1994; Lidz et al., 2003), geographical patterns of water circulation (Lee et al., 2001), residence time (Nuttle et al., 2000; Rudnick et al., 2005), bottom type, urban/agricultural and seagrass and/or mangrove coverage (Fourqurean et al., 2003; Simard et al., 2006).

Classification and grouping of south Florida coastal waters into spatial water quality (WQ) clusters have been performed by Boyer et al. (1997), and Briceño and Boyer (2010) in Florida Bay; by Caccia and Boyer (2005), Hunt and Todt (2006) and Boyer and Briceño (2008a,b) in Biscayne Bay; by Boyer and Briceño (2006) in the Whitewater Bay-Ten Thousand Islands region; and by Boyer and Briceño (2009) in the Florida Keys. These studies used a combination of Principal Component and Cluster Analysis for grouping the sampling sites, except in the work by Hunt and Todt (2006) where a direct cluster analysis of salinity and temperature was performed to group a pool of Miami-Dade County's Department of Environmental Research Management (DERM) and FIU stations. The proposed subdivision, presented here, incorporates additional data and extended period of record (POR). It has been designed to meet three long-range objectives: (1) to describe biogeochemical units that have certain homogeneous natural attributes; (2) to furnish units for inventory and mapping; and (3) to arrange these units in a system that will aid decisions about resource management, namely water quality and nutrient criteria.

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Finally, the health of South Florida's estuaries and coastal waters is critical not only for the preservation of its biodiversity, but also for supporting an important sector of Florida's industry that produces $100 billion a year in revenue and supports over 900,000 direct jobs generated through recreation, fishing, tourism and other water-linked activities state-wide (Visit Florida, 2012; FFWCC, 2012).

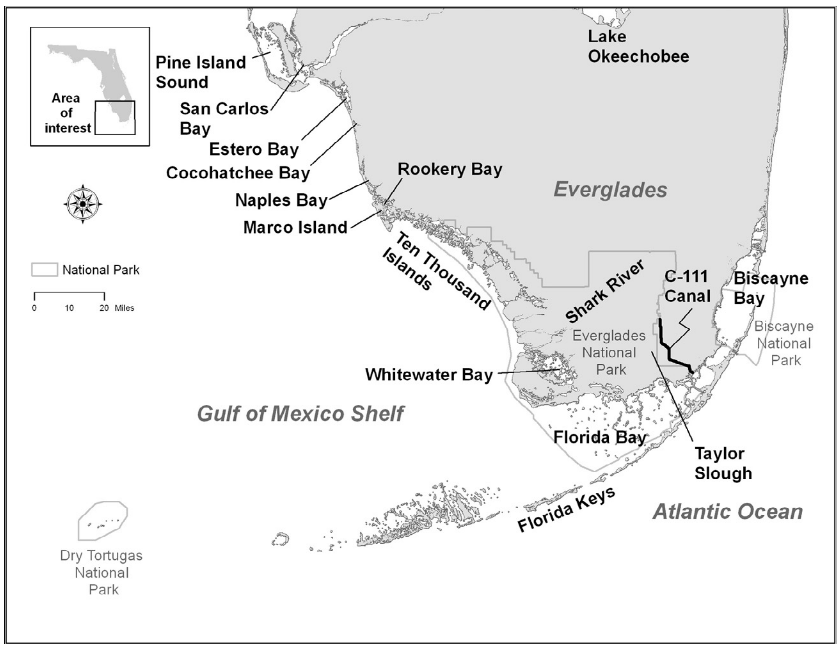

Fig. 1. South Florida's coasts and estuaries.

Table 1
Summary of inputs and results from segmentation analysis.

	Biscayne Bay	Florida Bay	Florida Keys	Whitewater Bay-10,000 Islands	Shelf	Southwest Florida
POR	Jun/96 to Sep/08	Mar/91 to Dec/07	Mar/95-Oct/09	Sep/92-Sep/08	May/95-Sep/07	Jan/99-Sep/09
Input variables for factor analysis	TN TP CHLA TOC SAL_S DO_S TURB NOX NO2 NH4 SRP	TN TP CHLA TOC SAL DO TURB TON NO3 NO2 NH4 SRP TEMP	TN TP CHLA TOC SAL DO TURB TEMP	TN TP CHLA TOC SAL DO TURB NH4	TN TP CHLA TOC SAL DO TURB NH4 NOX	TN TP CHLA TOC SAL_S DO_S TURB NO3 NO2 NH4 SRP
Stations	30	28	155	47	49	29
Factors	5	6	4	4	4	5
Acct Variance	73%	79%	66%	75%	63%	81%
Clusters	$n = 9$ Card Sound (CS) North-Central Inshore (NCI) North Central Outter (NCO) Northern North Bay (NNB) South Central Inshore (SCI) South Central Mid Bay (SCM) South Central Outter (SCO) Southern North Bay (SNB) Manatee-Barnes Sound (MBS)	$n = 6$ Central Florida B. (CFB) Eastern-Central (ECFB) North Florida B. (NFB) Coastal Lakes (CL) South Florida B. (SFB) West Florida B. (WFB)	$n = 7$ Back Bay (BKB) Back Shelf (BKS) Lower Keys (LK) Middle Keys (MK) Upper Keys (UK) Marquesas (MAR) Offshore (OFF)	$n = 8$ Black River (BR) Coastal Transition Z. (CTZ) Gulf Islands (GI) Internal Waterways (IWW) Mangrove Rivers (MR) Ponce de Leon (PD) Shark River Mouth (SRM) Whitewater Bay (WWB)	$n = 3$ Inner (IGS) Mid (MGS) Outter (OGS)	$n = 11$ Collier Inshore (CI) Estero Bay (EB) Marco Island (MARC) Naples Bay (NB) Pine Island S. (PINE) San Carlos B. (SCB) Cocohatchee (COCO) Rookery Bay (ROOK) Rookery B. South (RBS) Gullivan Bay (GB) Barfield Bay (BAR)

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Table 2
Factor loadings. Values in bold highlight controlling variables and values within parenthesis are % accounted variance.

	Florida Bay						Southwest Florida					Biscayne Bay				
	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
NOX												**0.841**	−0.071	−0.002	0.074	0.061
NO3	−0.131	**0.550**	0.031	0.080	0.012	−0.476	**0.743**	−0.059	0.064	−0.073	0.118					
NO2	−0.035	**0.836**	3.8E−04	−2.3E−05	−0.015	−1.5E−04	**0.788**	−0.102	−0.067	0.039	−0.016	**0.877**	0.026	−0.033	−0.033	0.043
NH4	0.178	**0.775**	−0.106	−0.009	0.021	0.158	**0.755**	−0.093	−0.402	0.086	−0.392	**0.709**	0.014	0.181	−0.186	−0.064
TN	**0.863**	0.192	−0.021	0.017	−0.024	0.053	0.136	0.049	−0.206	−0.118	**0.576**	0.275	−0.077	**0.711**	−0.043	−0.015
TON	**0.878**	−0.037	0.004	0.017	−0.032	0.036										
TP	0.065	−0.096	**0.735**	−0.042	0.136	0.080	0.332	−0.003	0.044	0.383	0.462	0.015	0.421	−0.011	−0.029	**0.599**
SRP	4.3E−04	0.009	0.010	0.009	**0.956**	−0.028	**0.725**	−0.216	0.148	−0.020	0.210	0.046	−0.123	0.065	0.001	**0.831**
CHLA	0.128	−0.200	**0.689**	−0.029	−0.021	−0.002	0.021	**0.814**	−0.004	0.216	−0.048	−0.057	**0.724**	0.146	0.032	0.258
TOC	**0.784**	−0.055	0.009	0.028	0.031	−0.113	0.494	0.450	−0.097	−0.164	0.124	−0.102	0.190	**0.859**	−0.054	0.065
SAL	−0.076	0.081	0.025	0.090	−0.031	**0.843**	−**0.657**	−0.444	−0.035	0.225	0.047	−0.472	−0.077	−0.500	−0.234	−0.087
TEMP	0.100	−0.087	−0.122	**0.868**	−0.038	−0.132										
DO	0.045	−0.122	−0.017	−**0.814**	−0.041	−0.166	0.122	0.002	**0.917**	−0.009	−0.113	−0.045	0.039	−0.020	**0.975**	−0.019
TURB	−0.192	0.197	**0.783**	−0.041	−0.111	−0.089	0.085	0.028	0.002	**0.918**	−0.041	−6.0E-05	**0.807**	0.009	0.021	−0.164

	Shelf				Ten Thousand Islands-Whitewater Bay				Florida Keys			
	Factor 1	Factor 2	Factor 3	Factor 4	Factor 1	Factor 2	Factor 3	Factor 4	Factor 1	Factor 2	Factor 3	Factor 4
NOX	**0.632**	0.061	−0.293	0.239								
NH4	0.119	−0.014	−0.082	**0.843**	0.125	0.018	0.000	**0.944**				
TN	−0.075	0.113	**0.548**	**0.666**	**0.854**	0.120	−0.088	−0.046	0.026	−0.013	**0.715**	0.257
TP	0.031	**0.803**	−0.183	0.041	−0.246	**0.758**	0.024	0.151	**0.749**	0.060	−0.087	0.305
CHLA	0.482	0.456	0.151	0.080	0.173	0.517	**0.715**	0.168	**0.677**	−7.2E−05	0.172	−0.251
TOC	0.374	0.192	0.347	0.119	**0.894**	−2.2E−04	0.048	0.110	0.206	0.193	**0.751**	−0.159
SAL	−**0.774**	0.096	−0.215	0.129	−**0.761**	0.221	−0.195	−0.185	0.001	0.123	0.083	**0.893**
TEMP									−0.015	**0.785**	0.279	0.219
DO	0.137	−0.053	**0.808**	−0.022	−0.021	−0.006	**0.793**	−0.096	−0.040	−**0.795**	0.071	0.028
TURB	−0.002	**0.829**	0.143	−0.009	0.076	**0.801**	0.245	−0.095	**0.683**	−0.159	0.169	−0.075

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1.1. Study area

Estuaries and coastal areas included in this study span from Fort Myers region (Gulf Coast) to the Dry Tortugas (westernmost tip of the Florida Keys), and to Biscayne Bay on the southeastern portion of the peninsula (Fig. 1). Estuarine portions of the region are characterized by their nonpoint source runoff, and are highly compartmentalized by geomorphology and circulation dynamics, making it difficult to study water biogeochemistry under standard schemes of estuarine ecology (Boyer et al., 1997). South of Pine Island Sound and San Carlos Bay (Fig. 1) there is a series of small and interconnected bays within the coastal mangrove forests, whose shores are lined with urban developments, canals and golf courses, extending south from Estero Bay to Marco Island. Further south are the Ten Thousand Islands and Whitewater Bay regions, which make up the largest mangrove forest in the Western Hemisphere, characterized by a complex pattern of mangrove covered islands cut by streams fed from the Everglades marshes and locally by canals. Florida Bay is located south of the Everglades, is open to the Gulf of Mexico Shelf along its western boundary, and is bordered by the Florida Keys in south. Florida Bay receives freshwater runoff from the Everglades marsh through Taylor Slough (central portion), the C-111 Canal degraded levee (northeast end), and the Shark River Slough (western portion).

The Florida Keys is an archipelago which stretches for 350 km from east of Miami to the Dry Tortugas in a southwesterly direc-

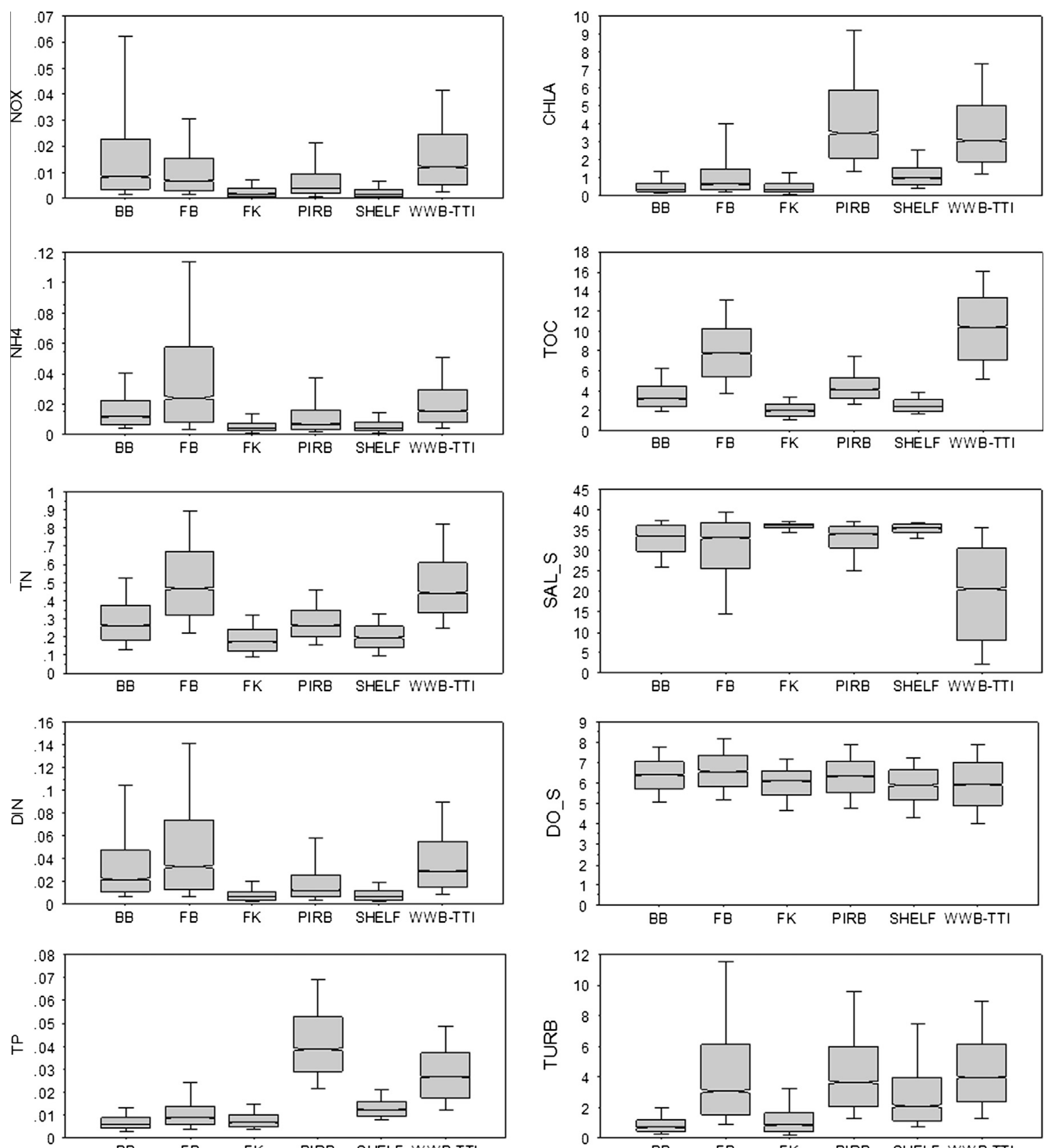

Fig. 2. Box-plots of selected biogeochemical WQ parameters to highlight diversity in coastal and estuarine waters of South Florida basins. BB = Biscayne Bay; FB = Florida Bay; FK = Florida Keys; WWB-TTI = Whitewater Bay-Ten Thousand Islands; SHELF = Gulf Shelf; and PIRB = Pine Island-Rookery Bay. Units are mg/l, except μg/l for CHLa; PSU for salinity; NTU for Turbidity; and °C for temperature.

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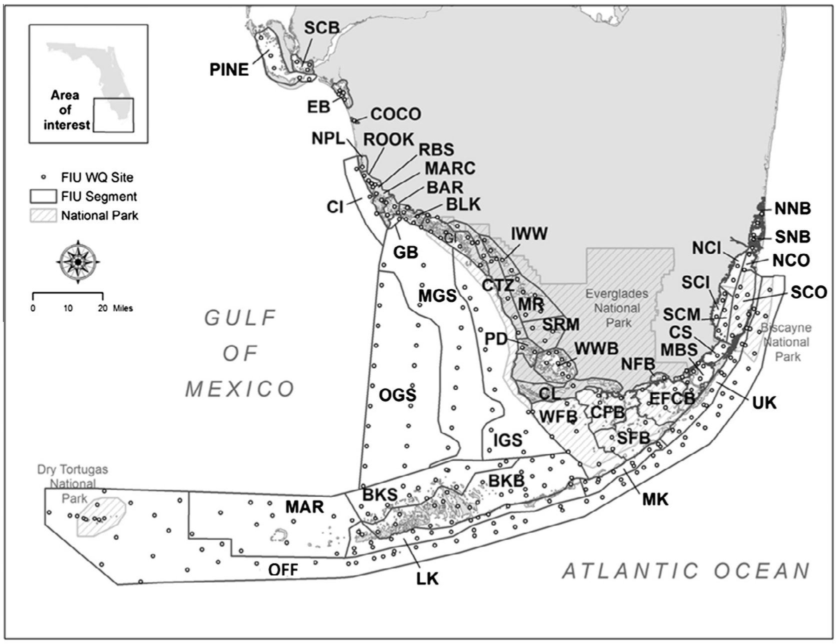

Fig. 3. Biogeochemical subdivision of South Florida coastal and estuarine waters.

tion. The Florida Keys exchange waters with the Gulf Shelf and Florida Bay to the north, and its southern coastline faces the Florida Straits and is bounded by the Gulf Stream. Finally, there is Biscayne Bay, a shallow coastal lagoon covering an area of approximately 700 km^2 adjacent to the City of Miami that has been subjected to constant human impact and highly managed freshwater supply.

2. Methods

2.1. Data sources

We selected a dataset generated by the South Florida Water Management District, the Environmental protection Agency (EPA) and Florida International University (FIU) because of its spatial–temporal coverage (353 stations), completeness of measured variables and its sustained field and analytical protocols along the period of record (POR). FIU WQ monitoring information was collected since 1991 for the Florida Bay stations, and since 1993 for most other stations elsewhere in South Florida. FIU WQ data were organized into six basins (Fig. 1): Biscayne Bay, Florida Bay, Whitewater Bay-Ten Thousand Islands and Pine Island Sound-Rookery Bay, which were sampled monthly; and the Florida Keys National Marine Sanctuary and Gulf Shelf, which were sampled quarterly. The data were directly downloaded from the Southeast Environmental Research Center (SERC) website (http://serc.fiu.edu/wqmnetwork/).

The FIU WQ monitoring samples were analyzed by SERC's NELAC Certified Water Quality Laboratory and included field measurements of surface and bottom salinity, temperature, dissolved oxygen (DO) and water clarity (Kd) and turbidity. Unfiltered surface water samples (10–50 cm depth) were analyzed for total organic carbon (TOC), total nitrogen (TN), total phosphorus (TP), and chlorophyll *a* (CHLa). Additionally, filtered surface water samples were analyzed for dissolved nutrients, including nitrate + nitrite (NO_x^-), nitrite (NO_2^-), ammonium (NH_4^+, inorganic nitrogen (DIN), soluble reactive phosphate (SRP), and silica (SiO_2). Some parameters were not measured directly, but were calculated by difference. Nitrate (NO_3^-) was calculated as NO_x^- minus NO_2^-, and dissolved inorganic nitrogen (DIN) was calculated as NO_x^- plus NH_4^+. Details of sampling methodology and laboratory analysis have been described elsewhere (Caccia and Boyer, 2005). Over 550,000 analytical results from the FIU WQ database were used for the segmentation analysis.

2.2. Statistical analysis

Our basin segmentation was accomplished following the objective analysis procedure of Boyer et al. (1997) to group sampling stations, combining Factor Analysis and Hierarchical Clustering methods in tandem. Factor Analysis is a multivariate method of data reduction, which uses orthogonal transformations to identify a reduced number of underlying variables (factors) that explain most of the variance observed (Overland and Preisendorfer, 1982).

Data were standardized (Z-scores) prior to Factor Analysis to reduce magnitude effects and the resulting Principal Component solution was Varimax-rotated to facilitate the interpretation (StatView®, Minitab 16®). Factor scores were retained for each station and their statistics were calculated. In our case, we selected 8–13 biogeochemical variables that were reduced to 4–6 factors for the six basins (Table 2). We used scree diagrams to help in the selection of principal components. In general, the magnitude of our retained eigenvalues was above 0.65 and the individual factor contributions to the accounted variances were above 5%. In order to account for both, magnitude and variability, we used parametric (mean, standard deviation) and non-parametric (median and median absolute deviation) of retained factor scores, at each station, as input into hierarchical clustering routines (Ward linkage with Euclidean distances;Minitab16®,SyStat®).

Initially, a unified PC-Cluster analysis was attempted for all six basins. The results of this analysis were not satisfactory because:

(1) The period of record (POR) had to be restricted to 1999–2007, when all stations were synchronously sampled (Table 1). Hence, a significant amount of data had to be discarded.
(2) Sampling frequencies were not uniform. Florida Keys and Shelf were sampled quarterly while the rest of the basins were sampled monthly. Adjusting to quarterly frequency caused lost of information for those basins sampled monthly

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(3) There are significant differences in concentrations of the analyzed species among basins, especially in nutrient concentrations. Small differences in oligotrophic waters (e.g. Florida Keys) are significant for discrimination and classification, but are overshadowed by the effect of nutrient enriched basins (e.g. Pine Island-Rookery Bay) when analyzed together.
(4) Only variables which contributed significantly to explain the overall variance were included in the analysis. Some were consistent contributors (TN, TP, CHLa, TOC, Salinity and DO; Table 1), while other varied among basins. These differences resulted in different number of input variables for the analysis.
(5) We established a maximum of 10% non-detects as criterion to include a given variable in the analysis at a given basin. This also caused differences in the number and kind of variables for each basin to be included in the analysis

In summary, given the asymmetries in biogeochemistry, POR and sampling frequency among basins, it was considered that combining all data in one large dataset would cause loss of important information and a significant increase in the variance to levels not necessarily related to the natural variability of individual watersheds. By analyzing each basin individually we optimized the discrimination by using only those variables and principal components which significantly contributed to explain the variance in the Factor Analysis. Additionally, local expert meetings organized by the FDEP also concluded that basins should be analyzed and classified separately because in many instances their ecosystem structure and functioning are significantly different.

3. Results

Compared to the rest of Florida, nutrient concentrations in South Florida coastal and estuarine waters are typically very low and display significant spatial–temporal variability, with water bodies responding differently to nutrient inputs (Fig. 2). Nitrogen species are high in those basins directly influenced by inland (i.e. Everglades) sources. Median TN values are low in the Florida Keys (FK) and Gulf Shelf (SHELF) (<0.198 mg/l), increase slightly in Biscayne Bay (BB) and Pine Island Sound-Rookery Bay (PIRB) (0.244–0.265 mg/l) and are even higher in basins immediately downstream from the Everglades, such as Florida Bay (FB) and Ten Thousand Islands-Whitewater Bay (TTI-WWB) (0.524–0.611 mg/l). Likewise, median DIN is very low in FK and SHELF (<0.007 mg/l), intermediate in TTI-WWB (0.028–0.033 mg/l), higher (>0.037 mg/l) in FB, and highly variable in BB and PIRB (0.013–0.021 mg/l). Median TP is low in BB, FK and FB (<0.009 mg/l) except in central FB (0.02 mg/l). The TP values are progressively higher in SHELF (0.012 mg/l), TTI-WWB (0.020–0.04 mg/l) and PIRB (0.039–0.065 mg/l). Median TOC is very low in FK (1.41 mg/l), BB (2.89 mg/l), and SHELF (2.47 mg/l) and increases drastically towards FB (7.75 mg/l) and TTI-WWB (8.1–13.3 mg/l). Median CHLa is very low in FK (0.22 μg/l) and BB (0.30 μg/l), except in northern BB (1.7 μg/l); CHLa is low (<0.9 μg/l) in SHELF, medium (0.7 μg/l) in FB, except in central FB (2.7 μg/l); and relatively high (2.7 and 7.7 μg/l) in TTI-WWB and PIRB.

3.1. Segmentation

Segmentation results for the six basins are summarized in Table 1. Selected Factors ranged from 4 to 6 and accounted from 63% to 81% of the variance. Biogeochemical variables making those factors were generally associated across south Florida, indicating a consistent biogeochemical link (Table 2), as follows: TN and TOC were regularly associated and were inversely related to salinity; TP, CHLa and turbidity, were often together in specific principal components; and DO was negatively linked to temperature. These relationships are similar to those reported by Boyer et al. (1997) for Florida Bay, and Caccia and Boyer (2005) for Florida Bay.

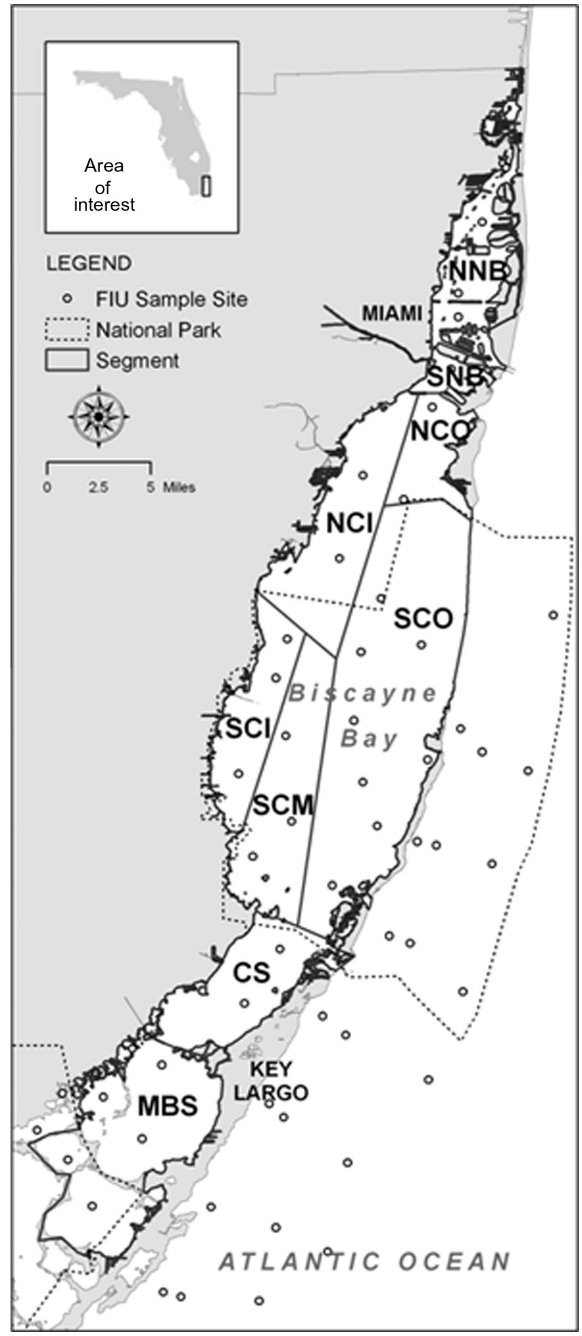

Fig. 4. Segmentation of Biscayne Bay. NNB = Northern North Bay; SNB = Southern North Bay; NCI = North-central Inshore; NCO = North-central Outer-Bay; SCI = South-central Inshore; SCM = South-central Mid-Bay; SCO = South-central Outer-Bay; CS = Card Sound; MBS = Manatee-Barnes Sound.

A total of forty-four sub-basins were established for South Florida coastal and estuarine waters and are shown in Fig. 3. We recognize that it is difficult to draw a border line separating segments within a continuous and non-static water body, where any contact is probably transitional. Once the spatial grouping was ascertained, segment boundaries were generated by multiple approaches based on geomorphology, bathymetry, circulation patterns, and best pro-

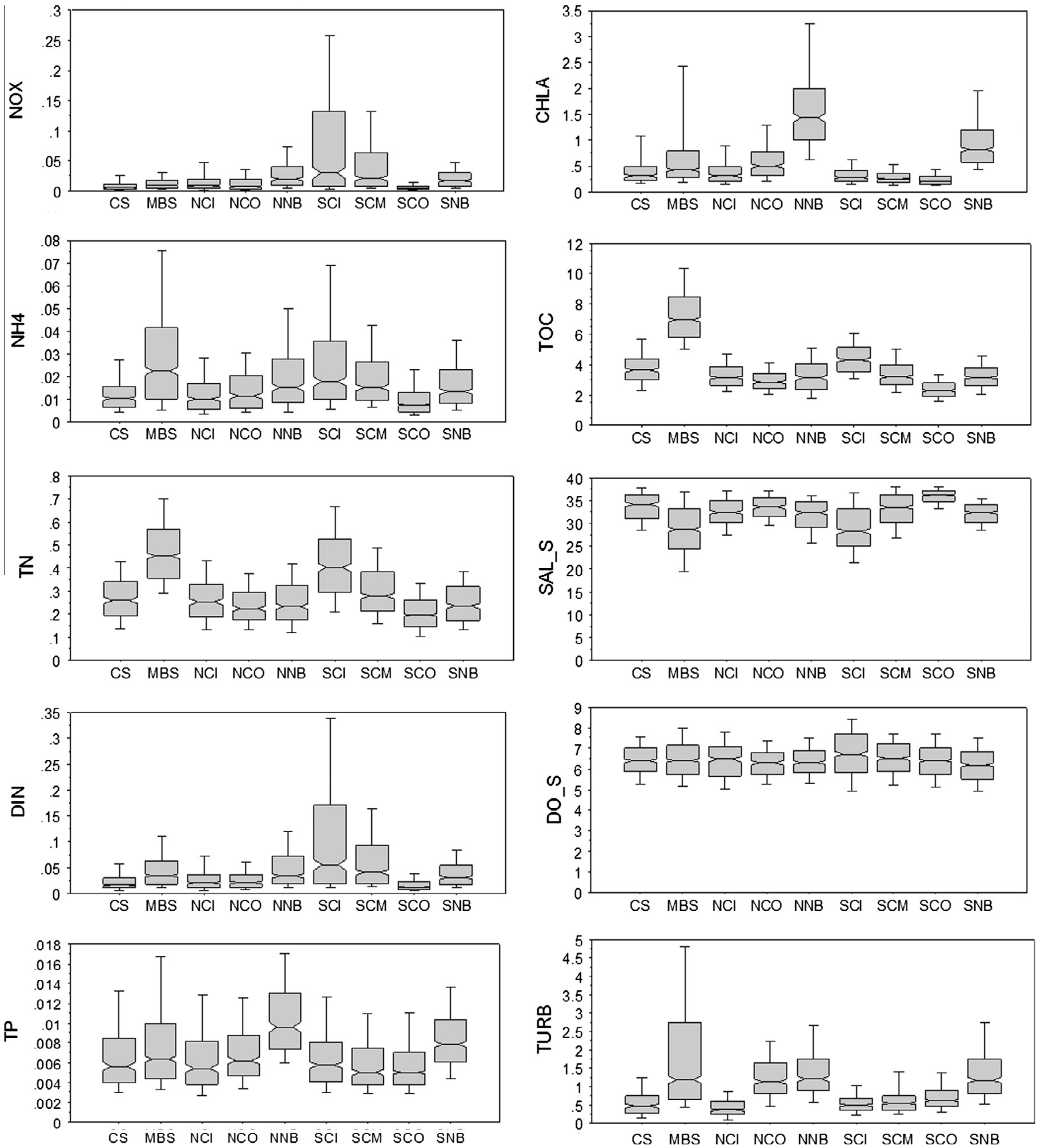

Fig. 5. Box-plots of WQ biogeochemical parameters in Biscayne Bay segments. Nutrient (TN, TP, TOC, DIN) and DO units are mg l^{-1}; chlorophyll-a (CHLA) in μl^{-1}; Turbidity (Turb) in NTU; and Salinity (Sal) in PSU. Abbreviations as in Fig 4.

fessional judgment. In the case of FB, TTI, and WWB, we followed the physical basin configurations as defined by the FATHOM Model (Cosby et al., 2005; Marshall et al., 2008). Segments in BB were drawn in accordance with bathymetry and known circulation patterns (Wang et al., 2003). Florida Keys National Marine Sanctuary (FKNMS) segmentation followed an onshore-offshore bathymetric feature of the reef being separated from inshore by broad Hawk Channel feature as well as consensus formed at the initiation of the FKNMS (Klein and Orlando, 1994). In some instances, segment boundaries were drawn as simplified straight lines to facilitate rule making. Drawing of borders for PIRB segments was very complicated, especially towards it southern portion. In general, besides biogeochemical differences, hydraulic connectivity, land use/cover and geomorphology played an important role.

There is general consensus among regional experts that this segmentation is representative of geochemical conditions of the area (FDEP, 2010b) but we must acknowledge that judgment based decisions were used. In summary, segment border lines are knowledge-based and site-specific and not the automatic result of spatial statistical analysis.

3.2. Biscayne Bay

Biscayne Bay is a shallow (0.5–3.0 m deep), well mixed subtropical coastal lagoon located along the eastern outskirts of the Great Miami Metropolitan area. BB surface freshwater supply is managed throughout a complex canal network draining into the estuary area of approximately 700 km^2 with a predominantly urban-agricultural watershed (2429 km^2; Roessler and Beardsley, 1974; CERP, 2010). The urban setting dominates towards the northern and north-central portions of Biscayne Bay, while agricultural activities concentrate in its south-central and southern regions (Irlandi et al.,

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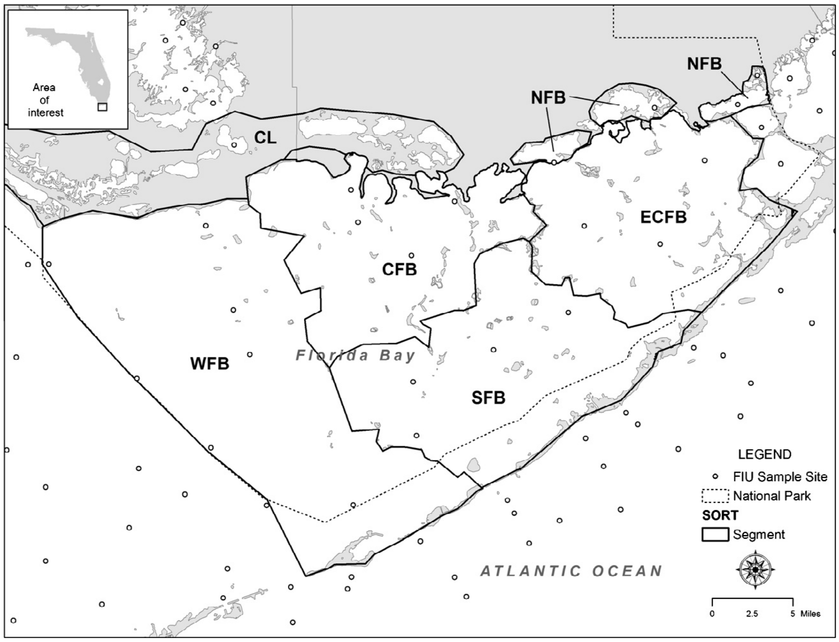

Fig. 6. Segmentation of Florida Bay. NFB = Northern Florida Bay; CL = Coastal Lakes; WFB = West Florida Bay; CFB = Central Florida Bay; SFB = South Florida Bay; ECFB = Eastern Central Florida Bay; MBS = Manatee-Barnes Sound.

2004; Caccia and Boyer, 2005, 2007). These differences in watershed makeup result in varied nutrient contributions to the Bay, with relatively elevated NO_x, TN and TOC loads from the southern agricultural areas into South Biscayne Bay, and high NH_3^- and TP loads from the northern and central urban areas into North Central BB and North BB (Lietz, 1999; Caccia and Boyer, 2007; Carey et al., 2011). Estuarine salinity ranges are observed only close to shore but most of the bay is experiencing long-term salinization (Bellmund et al., 2009).

The bottom of North BB is mostly bare substrate with areas of patchy or continuous seagrass restricted to the shallowest bottoms (Harlem, 1979) and in Central Bay seagrasses dominate over bare bottom (Irlandi et al., 2004). In South Central BB seagrass beds are extensive and bottom coverage makes up to 70% of the area, except in the middle bay where hard bottom dominates (70%). In the southern region (Card and Barnes Sound and Manatee Bay), seagrass is the dominant benthic type with 80% coverage (CERP, 2010). Benthic communities include several seagrass and macroalgae species and respond to prevailing salinity regime (Irlandi et al., 2002; Lirman and Cropper, 2003).

Our classification and grouping of BB waters into nine spatial WQ segments (Fig. 4) agrees with that previously obtained by Caccia and Boyer (2005) using different PORs and different variables, and even resembles that of Hunt and Todt (2006) where a direct cluster analysis of only salinity and temperature was performed to group a pool of DERM and FIU stations.

Within the Bay, Card Sound (CS) and north-central inshore (NCI) segments have similar biogeochemical characteristics, except for slightly higher TOC and turbidity in CS (Fig. 5). North-central outer bay (NCO) seems to be a transitional zone between the TP- and CHLa-enriched north BB (NNB and SNB) and the TN- and TOC-enriched central Bay (SCO and SCM), which underscores the connectivity under Rickenbacker Causeway Bridge. Turbidity in Manatee-Barnes Sound (MBS) and north-central outer bay (NCO) is high, suggesting maritime traffic effects, especially in NCO with vessel impacts from the Port of Miami. South-central inshore (SCI) waters stand-out with the highest TN, TOC and DIN concentrations, while presenting the highest variability and lowest salinity bay-wide. These characteristics are the result of pulsating water deliveries to SCI by canals draining agricultural areas (Caccia and Boyer, 2005, 2007; Carey et al., 2011). South-central mid-bay (SCM) waters are a mixture of fresher inshore waters (SCI) and more marine-influenced waters of the south-central outer-bay (SCO). Northern (NNB) and southern north-bay (SNB), which are fast freshwater-flushed areas, are affected by large exchange with marine waters of the Atlantic Ocean. Nutrient enriched waters from canals draining urban areas discharge into NNB and produced the highest TP and CHLa concentrations in Biscayne Bay (Fig. 5). Extensive dredging in north BB has created large stretches of bare muddy bottom that when combined with heavy traffic of boats and enhanced water agitation results in high turbidity levels (Harlem, 1979). Manatee-Barnes Sound (MBS) has the highest turbidity, TN, and TOC and lowest salinity levels in BB. Although hydraulically connected to BB, MBS is more biogeochemically related to FB. Stations within this segment make-up the Eastern Florida Bay segment (EFB) of Briceño and Boyer (2010).

3.3. Florida Bay

Florida Bay is a large (2000 km^2) and shallow estuary, with an average depth of 1.5 m (Hall et al., 2007) located at the southern end of the Florida Peninsula, between wetlands of the Everglades to the north and the Florida Keys to the south and east; its west side opens to the Gulf of Mexico (Fig. 6). Water exchanges with adjacent systems are driven by geomorphology, tidal forcing, wind stress, and circulation patterns of the Loop and Florida Currents (Lee and Williams, 1999; Gibson et al., 2008). Florida Bay is extensively compartmentalized into sub-basins separated by grassy mud banks which restrict water flow and tidal effects (Fourqurean and Robblee, 1999; Nuttle et al., 2000). The Bay receives freshwater runoff from the Everglades marsh through the C-111 Canal (northeast end), Taylor Slough (central portion), and indirectly from fresh water contributions from the Shark River Slough around Cape Sable into the western portion of the bay. The tidal prism is low with tidal effects restricted to its western and southern margins (Lee et al., 2001).

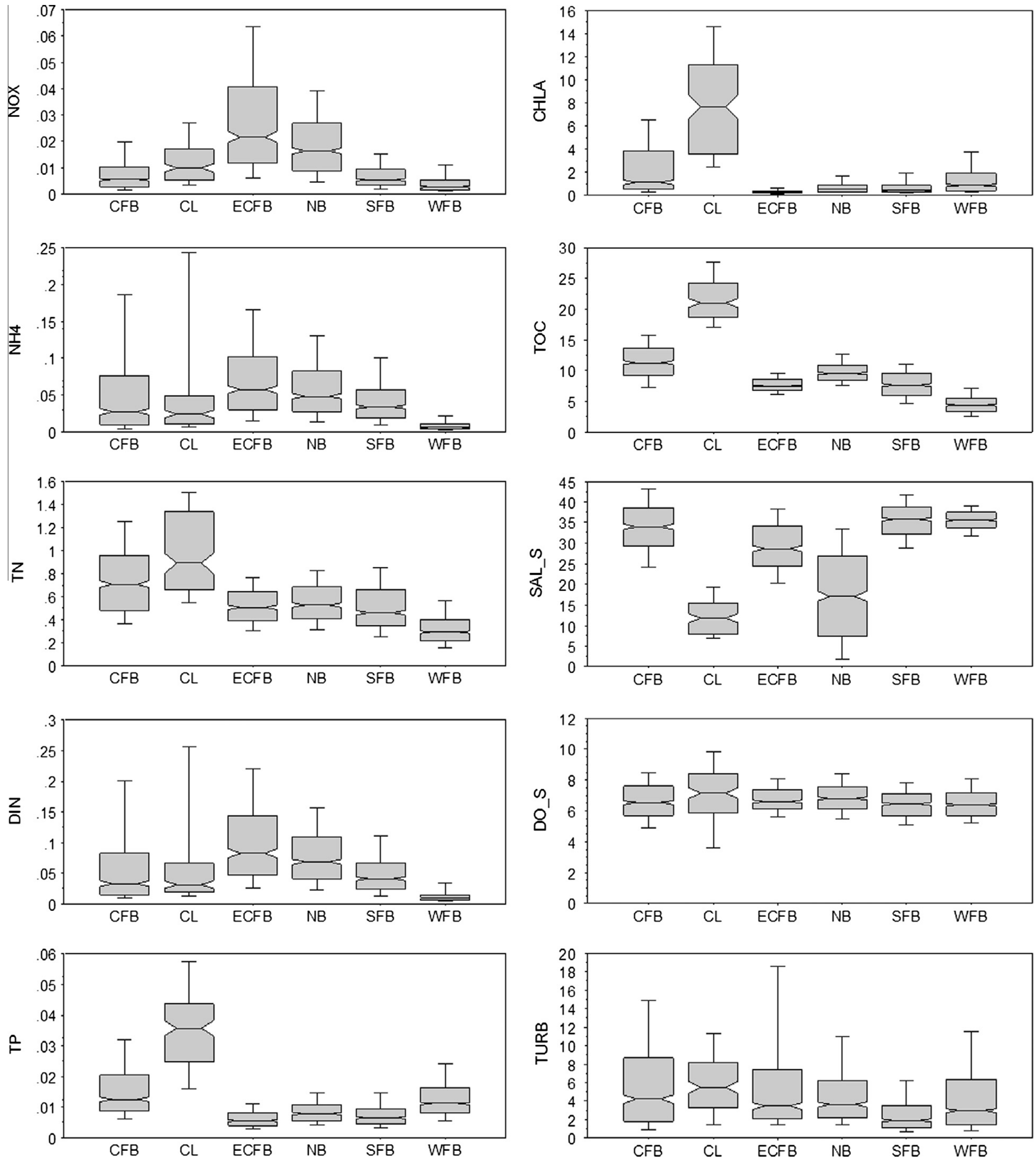

Fig. 7. Box-plots of WQ biogeochemical parameters in Florida Bay segments. Abbreviations as in Fig 6, and units as in Fig 5.

The recent subdivision of Florida Bay waters into six segments (Briceño and Boyer, 2010) matches very closely that of our segmentation with a larger POR, suggesting robust biogeochemical relationships. Box-plots in Fig. 7 summarize the biogeochemical characteristics of these six clusters. Two significant water-mixing gradients exist between freshwater draining from the Everglades on the north and either Gulf waters to the west or Atlantic waters to the southeast. The east–west and north–south gradients are affected by local evaporation in shallow, long residence-time sub-basins (e.g. CFB). Our biogeochemical clusters mimic very closely the divisions defined by benthic plant communities (Zieman et al., 1989; Fourqurean and Robblee, 1999) and by phytoplankton communities (Phlips et al., 1999). Central FB is the nutrient-richest segment, especially for TN, TP and TOC; has the highest CHLa and turbidity; and has extreme salinity values, suggesting that evaporation drives the enrichment processes. Eastern Central FB (ECFB) has the lowest TP and CHLa concentrations, but the highest inorganic-N (DIN) levels. Eastern FB (EFB) has the lowest levels of nutrients, CHLa and turbidity. The northern bays (NFB), which receive a substantial contribution of freshwater from the Everglades marsh, contain moderate to high nutrients and turbidity levels, low CHLa, and the lowest salinity bay-wide. In south FB (SFB), CHLa and

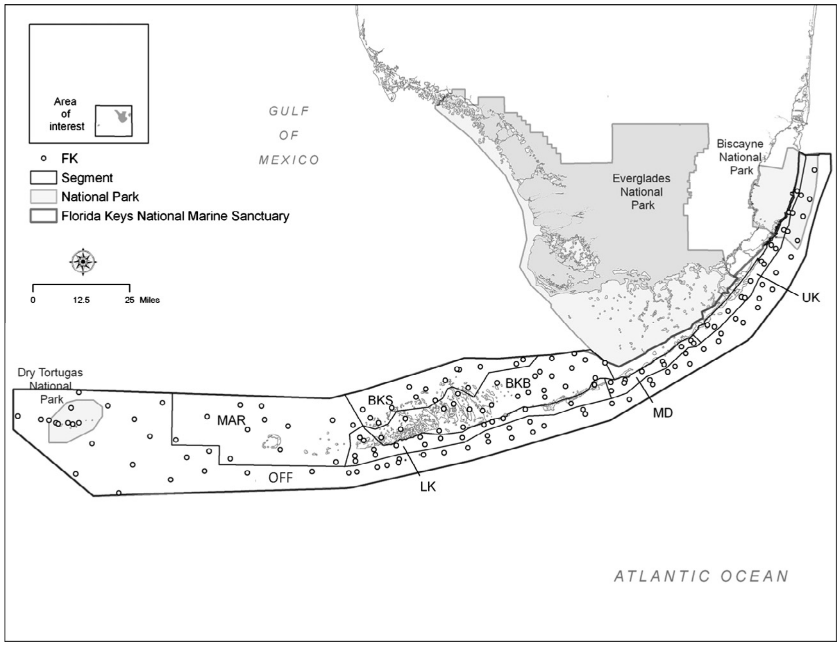

Fig. 8. Segmentation of Florida Keys National Marine Sanctuary. UK = Upper Keys; MK = Middle Keys; LK = Lower Keys; OFF = Offshore; MAR = Marquesas; BKB = Back Bay; BKS = Back Shelf.

turbidity are moderate and salinities are high, approaching marine water levels. West FB (WFB) displays the lowest TN, TOC and DIN concentrations, but relatively high TP, CHLa, turbidity and salinity (Fig. 7).

3.4. Florida Keys

The Florida Keys archipelago extends 350 km from eastern Biscayne Bay to the Dry Tortugas and is embraced by the 9500 square kilometers Florida Keys National Marine Sanctuary (FKNMS; Fig. 8). The Keys are bordered on the north and northwest by Everglades National Park and on the northeast by Biscayne National Park. Offshore of the Florida Keys is the Florida reef tract, the most extensive living coral reef system in North American and the third largest system in the world (Rohmann et al., 2005). The waters of the FK are characterized by complex water circulation patterns involving the Florida Current, the Gulf of Mexico Loop Current, inshore currents of the SW Florida Shelf, and by tidal exchange with both Florida Bay and Biscayne Bay (Lee and Williams, 1999; Lee et al., 2001). Water quality of the FK is directly affected both by external nutrient transport and internal nutrient loading sources (Gibson et al., 2008; Boyer and Briceño, 2011). On the ocean side, the Lower Keys are influenced by cyclonic gyres of the Florida Current, the Middle Keys by exchange with Florida Bay, and the Upper Keys by the Gulf Stream and by exchange with Biscayne Bay (FDEP, 2010a).

Seagrass beds in the FK are one of the largest and most continuous beds in the world (Fourqurean et al., 2012). These seagrass meadows, together with coral reefs, patch reefs, hardbottom and mangroves constitute the dominant habitats that make up the coastal marine ecosystems of the FK, occupying about 70%, 7%, 1%, 19% and 3%, respectively (Fourqurean et al., 2003). Although there have been changes in some communities (e.g. epiphytes, corals), causes other than nutrients (e.g. temperature) seem to be responsible for those changes (Lirman and Fong, 2007; Donahue et al., 2008; FDEP, 2010a). Near shore benthic communities have experienced very little variation through the past 40 years, despite the significant land development in the FK. Calcareous algae have increased over time and are more common close to land where DIN concentrations are higher (Lapointe et al., 2004; Collado-Vides et al., 2005, 2007).

Waters of the FK are oligotrophic with higher turbidity and nutrient concentrations on the Gulf of Mexico side of the Keys (BKS, BKB, MAR; Fig. 8) than on the Atlantic side, along the reef tract (LK, MK, UK and OFF), and Dry Tortugas region (Fig. 9). Land-based sources of nutrients in the Keys are principally from stormwater and wastewater injection wells (Lapointe et al., 1990, 2004; Boyer and Jones, 2001; Reich et al., 2001), but marine sources driven by advection are perhaps more important than land sources that shape the regional water quality (Boyer and Briceño 2006, 2011). Relatively small freshwater runoff and groundwater contributions are rapidly diluted by marine waters and their effects are mostly perceived very close to shore. Relatively elevated nitrate and DIN in the inshore waters of the Keys are a characteristic of ecosystems impacted by anthropogenic intervention (e.g. LK, MK and UK vs OFF in Fig. 9), suggesting an inshore source which is diluted by low nutrient Atlantic Ocean waters. The presence of a similar gradient in TOC and decreased variability in salinity from land to reef also support this concept. No trends are observed in either TP or CHLa with distance from land (Boyer and Briceño, 2011).

3.5. Ten Thousand Islands-Whitewater Bay

The Ten Thousand Islands-Whitewater Bay region (TTI-WWB; Fig. 10) includes a chain of mangrove covered islands off the coast of southwest Florida, extending between Cape Romano and Whitewater Bay, south of the Everglades freshwater marshes. A large percentage of the region is within the Ten Thousand Island National Wildlife Refuge and Everglades National Park. These protected areas are part of the largest expanses of mangrove forest in North America. Mangrove forests is the dominate vegetation in most tidal fringes and the numerous islands, and the rest consists of salt marsh with interspersed ponds and small coastal hammocks. Sources of waters and nutrients to the TTI-WWB include inputs from the Everglades marsh, the Gulf of Mexico, atmo-

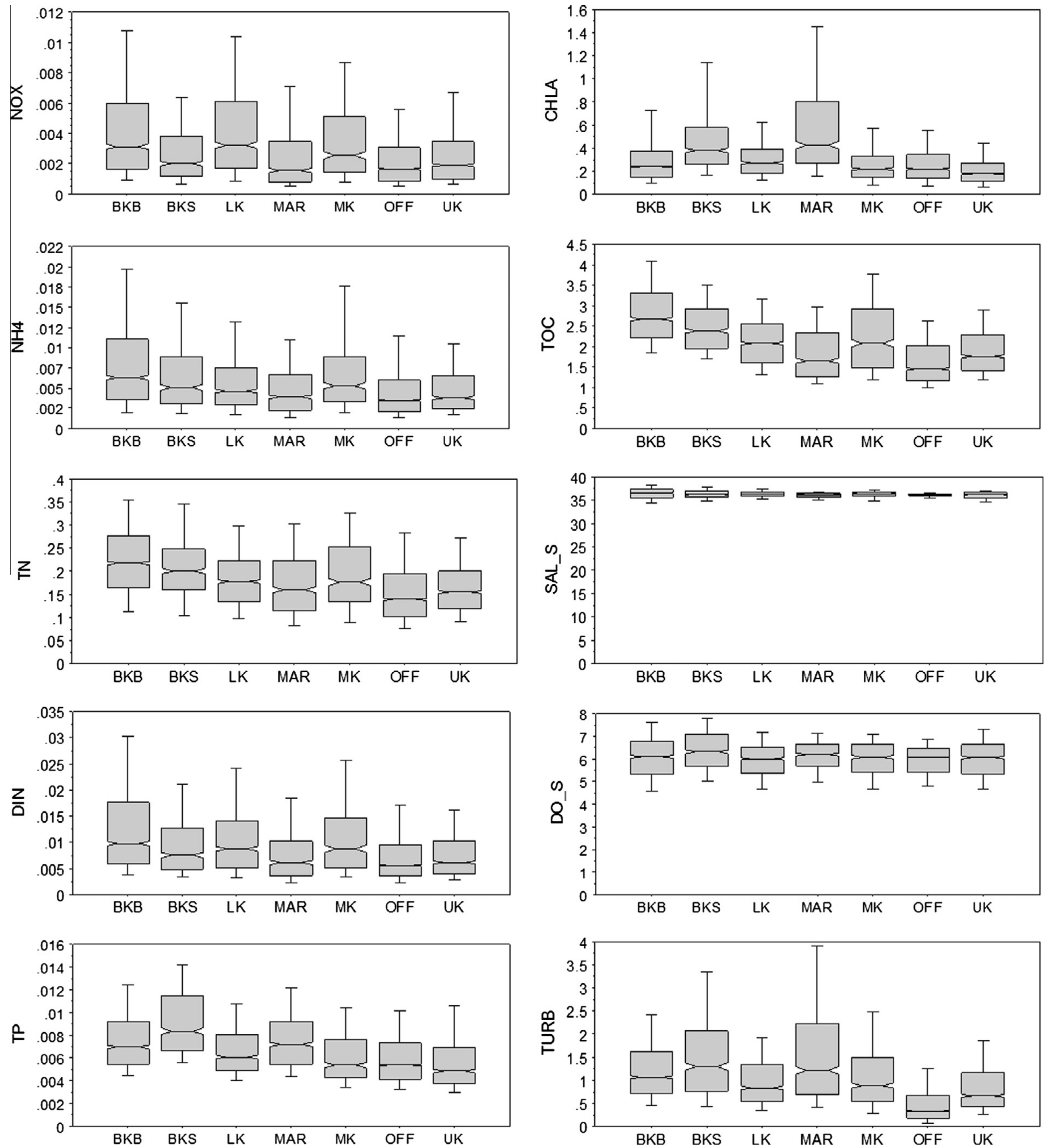

Fig. 9. Box-plots of WQ biogeochemical parameters in Florida Keys segments. Units as in Fig 5 and abbreviations as in Fig 8.

spheric deposition, and groundwater (Price and Swart, 2006; Boyer and Keller, 2007; FDEP, 2010b). Freshwater from the Everglades watershed enters as sheet flow especially through the Faka Union Canal, and the Blackwater, Broad, Harney, and Shark rivers (Boyer and Keller, 2007; Soderqvist and Patiño, 2010). Upstream changes in land use have driven increased nonpoint source runoff to the Everglades from urban and agricultural areas as far north as Lake Okeechobee (Lapointe and Clark, 1992).

Salinity and nutrients in the TTI-WWB region display two clear gradients (Figs. 10 and 11): first, salinity increases and TN decreases from inland to offshore (NE to SW), and second, salinity and TP decrease from the northwestern end (BLK) of the basin to the southeastern end (WWB) of the basin. The net effect on nutrients is the formation of a gradient with strong P limitation, (high N:P ratio) occurring in the southeastern region which shifts to a more balanced N:P ratio in the northern area around the Blackwater River. This trend is the result of complex exchange dynamics driven by coastal geomorphology, watershed characteristics and ecosystem structure as expressed by vegetation patterns (Simard et al., 2006; Boyer and Briceño, 2007). Southeastward from Marco Island to Everglades City small mangrove-covered islands with quartz-rich soils (BLK and GI) parallel a narrow belt, about 4 km wide, of coastal mangrove forest (CTZ), characterized by >4 m canopy and high standing biomass (60–175 Mg/ha; Simard et al., 2006). Continuing southeast the mangrove forest widens (15 km) and is characterized by <4 m canopy and lower standing biomass (25–60 Mg/ha) on the landward side (IWW, MR and SRM). Also small islands progressively disappear while soils become more calcareous and less quartz-rich (CTZ) and waters turn fresher (IWW, MR and SRM). Further south, peak canopy elevation (>18 m) and

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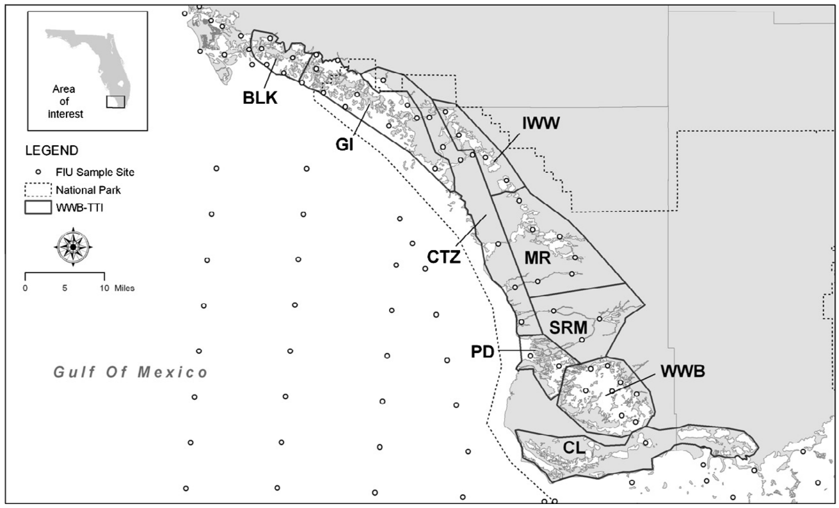

Fig. 10. Segmentation of the Ten Thousand Islands-Whitewater Bay region. BLK = Black River; GI = Gulf Islands; IWW: Internal Waterways; CTZ = Coastal Transition Zone; MR = Mangrove Rivers; PD = Ponce de Leon; SRM = Shark River Mouth; WWB = Whitewater Bay.

standing biomass (200 Mg/ha) increase (PD). Finally, at the end of this region is Whitewater Bay, a semi-enclosed body of water with a relatively long residence time. The bay is downstream from a low canopy mangrove forest (<4 m), and receives overland freshwater input from the Everglades marsh.

Similar spatial patterns to those of mangrove height and biomass are observed in salinity. These patterns are due to mixing of Everglades' freshwaters with Gulf of Mexico waters and groundwaters (Soderqvist and Patiño, 2010); to progressive soil-P enrichment from SE to NW (Boyer and Briceño, 2007); and to high mangrove productivity, where annual net primary production ranges from 1173 to 2066 g C m^{-2} yr^{-1} (Boyer and Briceño, 2006; Rivera-Monroy et al., 2011). Large salinity variations in the Everglades mangrove ecotone are common, and are driven by both water management practices and climatic events. Organic and inorganic nitrogen species are supplied in rather high concentrations by streams draining the Everglades marshes and mangrove forest, while phosphorus contributions are very low as compared to Gulf of Mexico waters. Hence, a northeast to southwest declining TN gradient develops as TP and salinity increase (Fig. 11). These loadings are strongly affected by seasonal variability and are closely linked to wetland productivity (Light and Dineen, 1994; Rivera-Monroy et al., 2011).

The Coastal Lakes (CL) are estuarine mangrove lakes and coastal embayments located along the northwest shore of FB and south of WWB (Fig. 10). Lake water chemistry deviates considerably from those of surrounding waterbodies. These lakes suffered major changes during the last century and experienced significant reduction of submerged aquatic vegetation, waterfowl and wading bird abundances from historical (1931–1946) levels (Davis and Ogden, 1994; Frankovich et al., 2010). These reductions parallel increasing salinities due to diminished freshwater inflows (Light and Dineen, 1994), as well as increasing TN, TOC, TP, DIN, turbidity and CHLa levels (Fig. 11).

3.6. Pine Island-Rookery Bay

The Southwest Florida basin extends southwards from Pine Island Sound to Cape Romano and includes a series of interconnected bays within mangrove forests whose shores are locally lined with urban developments, canals and golf courses, extending south across Estero Bay, Cocohatchee Bay, Naples Bay, Rookery Bay and Marco Island (Fig. 12). Vertical seawalls and bulkheads have replaced mangroves and salt marshes, so environmental impacts from this intense human intervention are dramatic, i.e. Naples Bay has lost 90% of its seagrass beds, 80% of its oyster reefs, and 70% of its mangroves since 1950 (FDEP, 2010b). Regionally, the most common habitats are mangroves, seagrasses and salt marshes. Fresh water deliveries from canals have greatly altered the natural salinity and nutrient regimes in the estuaries, especially releases from the Caloosahatchee River and associated pathways for the purpose of lowering the Lake Okeechobee's level and the water table to avoid flooding. Freshwater releases begin in June–July and cause rapid declines in salinity across the region, especially in San Carlos Bay (mouth of Caloosahatchee River), Rookery Bay, and the Cocohatchee River at Wiggins Pass. Also waters from San Carlos Bay and the Peace River contribute freshwater to Pine Island Sound via Charlotte Harbor. These large freshwater inputs typically result in high loads and concentrations of DIN, TOC and TP, (Fig. 13). In turn, these large and rapid increases in nutrient loading are suspected to cause large phytoplankton blooms (high CHLa) across the region.

There are seven water types which make eleven individual segments (Fig. 12) as follows: Type 1 = Cocohatchee; Type 2 = Rookery Bay South and Barfield Bay; Type 3 = Collier Inshore; Type 4 = Estero Bay, Naples Bay, Marco Island and Gulliver Bay; Type 5 = Pine Island Sound; Type 6 = Rookery Bay; and Type 7 = San Carlos Bay.

Overall, this part of coastal south Florida has significantly higher concentrations of CHLa, TP, and DIN than the Ten Thousand Islands to the south. Much of this is due to human impact driven by major land use changes towards more urban and agricultural development and less natural marshland, and also because of geological changes from carbonate to mostly silica-rich sediments, which facilitates the transport of phosphorous. Potential sources of nutrients to the estuaries include phosphate mining and agricultural activities, stormwater runoff from both natural and urban areas, atmospheric deposition, and point source discharges (FDEP, 2010b). San Carlos Bay (SCB) and Cocohatchee (COCO) are most affected by fresh water releases and have the highest concentrations of TN, TP, DIN, and TOC (Fig. 13). This suggests that run-off is perhaps the main source of nutrients. Estero Bay (EB) exhibits moderated salinities as a result of freshwater input from the Estero River and Imperial River as well as Hendry Creek. It is relatively enclosed, has a long water residence time and is bordered on the north by the city of Ft. Meyers. These facts may contribute to moderate to high levels of CHLA, DIN and TP (Fig. 13). Chlorophyll and turbidity are higher in areas mostly affected by urban development (BFB, RBS, MARC, ROOK, and COCO).

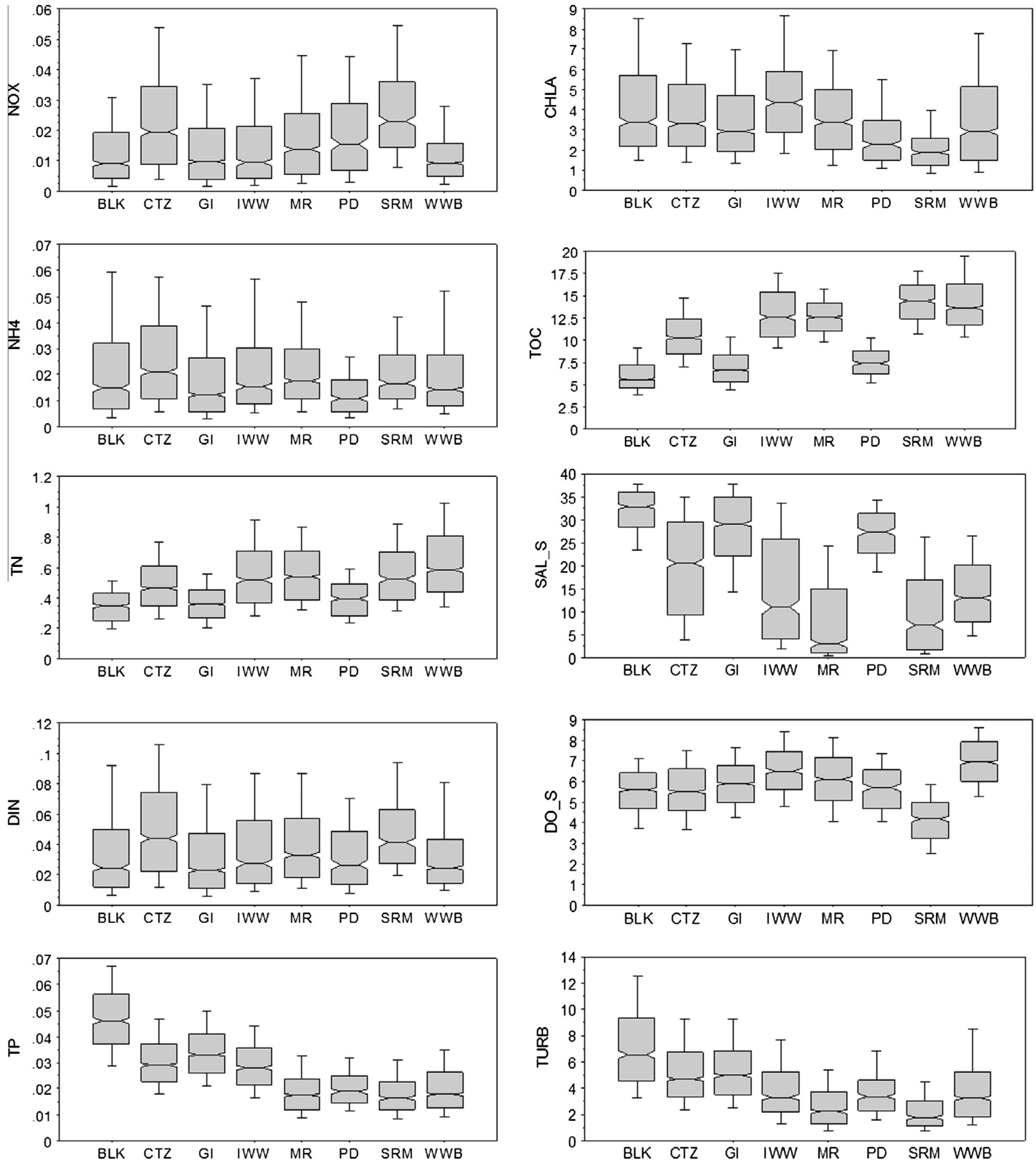

Fig. 11. Box-plots of WQ biogeochemical parameters in Ten Thousand Islands-Whitewater Bay segments. Units as in Fig 5 and abbreviations as in Fig 10.

3.7. Gulf Shelf

The Southwest Florida Shelf (SWFS) located on the western side of the Florida Peninsula, is one of North America's broadest continental shelves (up to 270 km wide). Regionally, shelf break currents are largely controlled by the Loop Current while those on the SWFS are largely controlled by local winds (Weisberg and He, 2003), and their combined influence account for most of the inter-annual variability of circulation. That portion of SWFS studied here is referred to as the Gulf Shelf (SHELF; Fig. 14) and includes depths shallower than 20 m whose exchange is with the TTI-WWB to the north, Florida Bay (WFB) to the east, wind-driven SWFS water masses on the west, and with the Florida Keys (BKS and MAR) at its southern boundary. The SHELF is characterized by a layer of fine-grained sediment over bedrock with small localized areas of outcrops (Mahmoudi et al., 2002). Water overlying the northern SHELF stations probably originates somewhere in or north of the Ten Thousand Islands (i.e. Tampa-Marco Island). In the north, rivers and canals -located or connected to wetlands-drain phosphorous-rich bedrock and phosphate mining areas and contribute significant TP loads to Tampa Bay and Charlotte Harbor. These waters eventually flow south transporting the nutrients into the SHELF (Hu et al., 2004). Freshwater from Shark River also interacts with SHELF. They flow south into the SHELF and then east

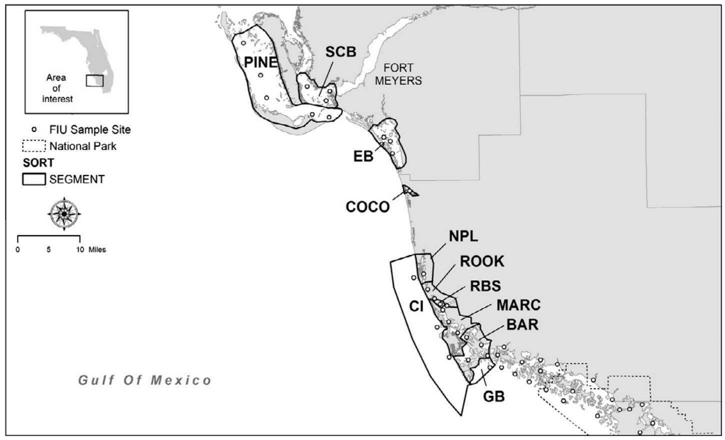

Fig. 12. Segmentation of Southwest Florida Basin (Pine Island-Rookery Bay region). PINE = Pine Island; SCB = San Carlos Bay; EB = Estero Bay; COCO = Cocohatchee; CI = Collier Inshore; NPL = Naples; ROOK = Rookery Bay; RBS = Rookery Bay South; MARC = Marco Island ; BAR = Barfield Bay; GB = Gulliver Bay.

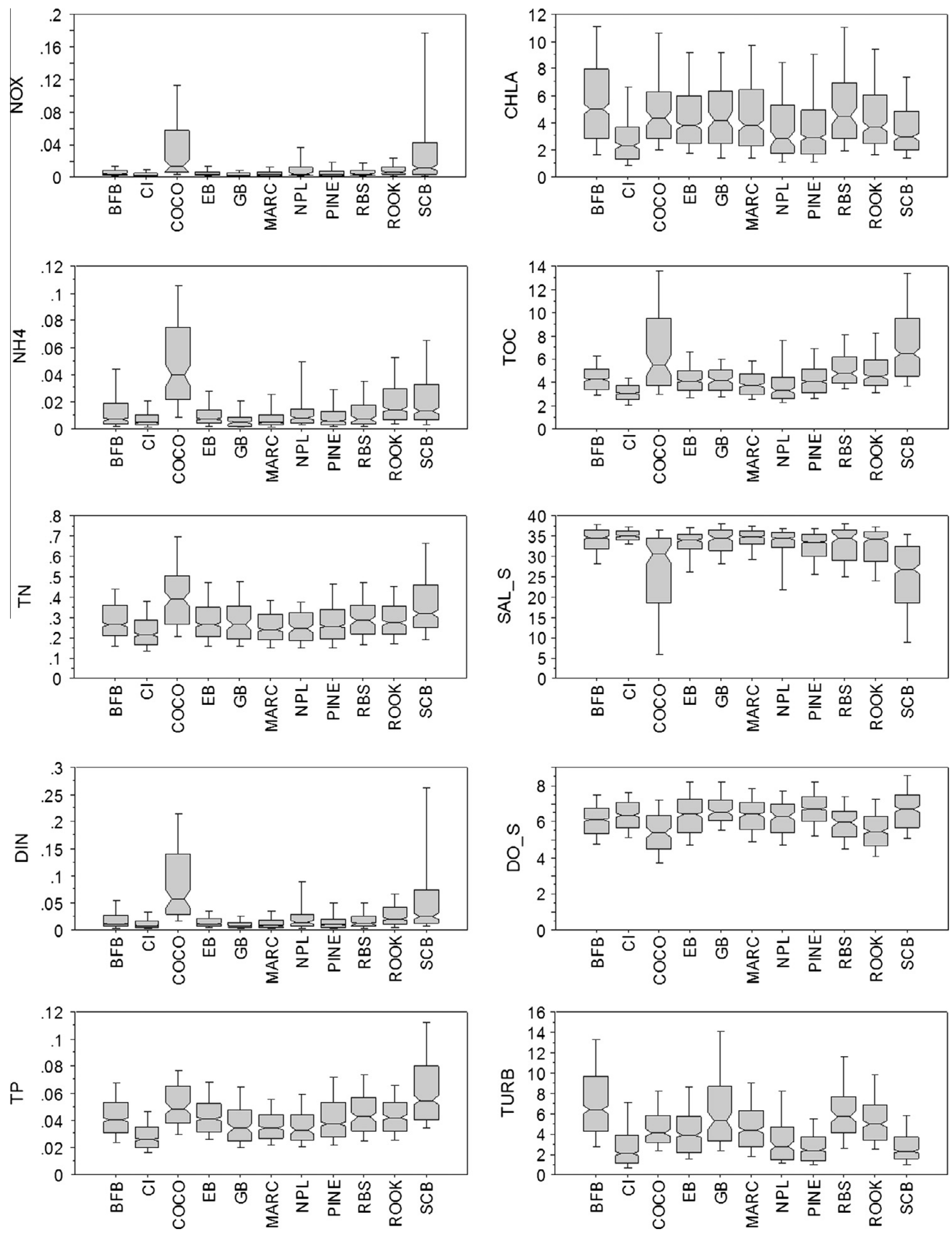

Fig. 13. Box-plots of WQ biogeochemical parameters in Southwest Florida segments. Units as in Fig 5 and abbreviations as in Fig 12.

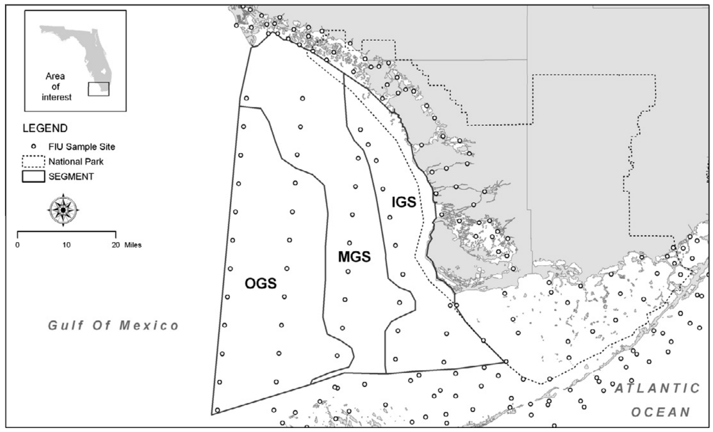

Fig. 14. Segmentation of Gulf Shelf waters. OGS = Outer Gulf Shelf; MGS = Mid Gulf Shelf; IGS = Inner Gulf Shelf.

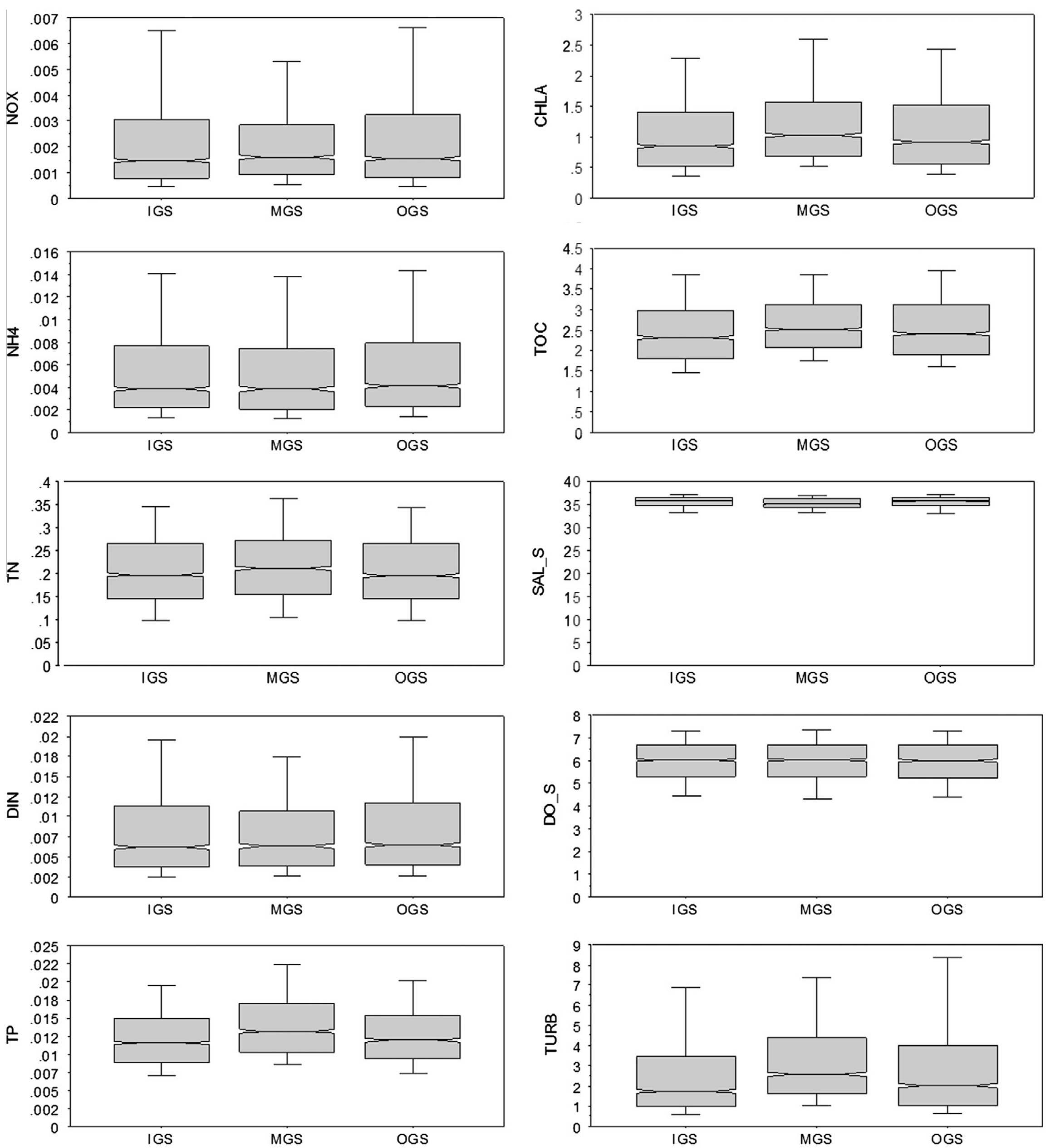

Fig. 15. Box-plots of WQ biogeochemical parameters in Gulf Shelf segments. Units as in Fig 5 and abbreviations as in Fig 14.

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around Cape Sable into Florida Bay (Rudnick et al., 1999; Boyer and Briceño, 2006).

Ninety percent of marine plant species on the SWFS are macroalgae (Earle, 1972) underscoring the importance of macroalgae to marine organic primary productivity. The seagrasses in the SHELF region are comprised mainly of Halophila decipiens and Thalassia testudinum (SERL, 2011). The SHELF phytoplankton consists mainly of diatoms and dinoflagellates, whose productivity and standing crop are associated to P-rich upwelling (Austin and Jones, 1971) and/or P-rich freshwater inputs (Boyer and Briceño, 2006). Total nitrogen, TP, TOC, DIN, CHLa and turbidity follow a declining trend from Inner Gulf (IGS) to Outer Gulf Shelf (OGS; Fig. 15). On the other hand, salinity increases offshore towards OGS. Considering the preferential north–south current direction in the SHELF, the relationships seem to indicate that the SHELF is strongly influenced by external nutrient sources which may be located either in TTI-WWB and/or further north in PIRB (Boyer and Briceño, 2006; Boyer and Briceño, 2008a,b).

4. Conclusions

Our objective was to generate a spatial–temporal characterization and classification of South Florida's estuarine and coastal waters. Our results, on the other hand, are intended to fill gaps in the information and science necessary to underpin good planning and decision-making in water management. Our research attempts to inform the design of relevant and effective institutional arrangements, including regulations and policies designed to preserve water and environmental quality. In this context, spatial–temporal characterization of South Florida's estuarine and coastal waters is important to Everglades' restoration programs and necessary for the current derivation of numeric nutrient criteria by federal and state agencies.

The segmentation we presented followed an ecological, multivariate approach which incorporated both, magnitude and variability of the biogeochemical descriptors of ecosystem status. The results of the statistical analyses described here would provide the foundation for the State of Florida to derive criteria as mandated by the US Environmental Protection Agency.

Results from the Factor and Cluster analyses for the six South Florida basins indicate that biogeochemical variables making those factors are generally associated across South Florida, suggesting that regional water quality patterns are defined by specific relationships and are not random. Freshwater marshes and mangrove forest seem to be the main source of organic and inorganic nitrogen, given that TN and TOC were regularly associated and were inversely related to salinity. Furthermore, most of the nitrogen is organic nitrogen (Rudnick et al., 1999). Total phosphorous and CHLa were consistently together in specific principal components, highlighting the limiting effect of TP on phytoplankton productivity region wide. Although TP, CHLa and turbidity were related, CHLa concentrations were too small to account for turbidity variations; hence, turbidity may be linked to sediment re-suspension instead, and TP released from those suspended sediments is perhaps the driver of CHLa production (Caccia and Boyer, 2007). Finally, DO is negatively correlated with temperature, and NH4 is negatively related to salinity.

As expected, the segmentation mimicked very closely the geographical patterns observed in South Florida, resulting from a combination of: geomorphology and geology (Wanless and Tagett, 1988); water circulation and residence time regimes (Wang et al., 1994, 2003, 2007; Brand, 2001; Cosby et al., 2005); salinity distribution (Nuttle et al., 2000; Cosby et al., 2005; Kelble et al., 2007; Bellmund et al., 2009; Soderqvist and Patiño, 2010); TP and TN concentrations and loads (Fourqurean et al., 1993; Fourqurean and Robblee, 1999; Hitchcock et al., 2007); spatiotemporal patterns of seagrass distribution (Zieman et al., 1989; Zieman and Zieman, 1991; Roblee et al., 1991; Fourqurean et al., 2003); phytoplankton types and biovolumes (Phlips and Badylak, 1996; Phlips et al., 1999; Steidinger et al., 2001; Hunt and Nuttle, 2007; Kelble et al., 2010); and benthic communities in general (Turney and Perkins, 1972; Torres, 2007; CERP, 2010). One of the major strengths of the analysis is that it was conducted based on data collected by a single entity, FIU, but we must recognize that there is increased uncertainty in the representativeness of the segmentation near the periphery of the basins and where there is low station density. Furthermore, the cluster analysis provides discrete station groupings and is thus very useful for establishing homogenous segmentation. However, nature does not typically operate in discrete units, although the current regulatory structure tends to view it as such.

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