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Climatic Controls on Phytoplankton Biomass in a Sub-tropical Estuary, Florida Bay, USA

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Abstract The extraction of climatic signals from time series of biogeochemical data is further complicated in estuarine regions because of the dynamic interaction of land, ocean, and atmosphere. We explored the behavior of potential global and regional climatic stressors to isolate specific shifts or trends, which could have a forcing role on the behavior of biogeochemical descriptors of water quality and phytoplankton biomass from Florida Bay, as an example of a sub-tropical estuary. We performed statistical analysis and subdivided the bay into six zones having unique biogeochemical characteristics. Significant shifts in the drivers were identified in all the chlorophyll *a* time series. Chlorophyll *a* concentrations closely follow global forcing and display a generalized declining trend on which seasonal oscillations are superimposed, and it is only interrupted by events of sudden increase triggered by storms which are followed by a relatively rapid return to pre-event conditions trailing again the long-term trend.

Keywords Florida Bay · Chlorophyll *a* · Time series · Climate signal · CUSUM · Hurricane impact

Introduction

Two of the most important challenges in global change ecological research are the ability to detect ecosystem changes and directly tie them to changes in pertinent environmental drivers. This is especially true when dealing with phytoplankton, as individuals and populations vary over weeks and communities vary over seasonal and annual cycles. Understanding the temporal variability in phytoplankton community composition and biomass has been a central focus in marine ecology for many years (Steele and Henderson 1981). Since domination of an individual species or community type may only last for a few weeks and occur at specific times of the year suggests that variability of both endogenous and exogenous factors play a regulatory role (Belgrano et al. 2004).

Most data sets generated during surveys and monitoring programs are interpreted using time series, where one of the axes is either time or distance. Due to the inherently complex character of natural phenomena, data are strongly affected by serial correlation and high variability can mask underlying patterns (trends, shifts, cycles, and seasonal variations). A battery of statistical techniques to study time series has been developed in the field of electrical signal analysis, economics, and quality control (Box et al. 1994; Chatfield 1996; Manson and Lind 1996; Emery and Thomson 2001). However, one difference in time series used in engineering and environmental sciences is that the latter rarely use data collected at regular intervals, either in time or space. Hence, it is normally necessary to perform a pre-treatment of the data sequence before attempting more orthodox statistical tests (Sturges 1983; Box et al. 1994; Chatfield 1996; Emery and Thomson 2001). Another problem is that climate-related time series usually contain combinations of variables measured at different time scales and at variable locations.

In the present study we attempt to link biogeochemical descriptors of water quality to external drivers, both natural and anthropogenic, using contrasting time series methods. Florida Bay is used as an example of a sub-tropical estuary. Statistical analyses were used to subdivide the bay into

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zones of similar biogeochemical characteristics. Changes in the character of the zones since 1989 were investigated within the context of global and regional climatic stressors such as North Atlantic oscillation (NAO), Atlantic multidecadal oscillation (AMO), local rates of precipitation, storms, accumulated cyclone energy (ACE), and variations in freshwater supply from the Everglades. The responses of the phytoplankton biomass focused on changes in chlorophyll *a* concentrations (CHLA).

Methods

Site Description

Florida Bay is a large (2,000 km^2) and shallow (average depth 1.5 m) estuarine lagoon located at the southern end of the Florida Peninsula (ca. 25º 05' N, 80º 45' W), between wetlands of the Everglades to the north and the Florida Keys to the south and east; on the west side it is open to the Gulf of Mexico (Fig. 1). Florida Bay includes numerous basins separated by grassy mud banks and except along its western portion, tides have little effect on the water levels in the bay, because the mud banks restrict water flow (Fourqurean and Robblee 1999; Nuttle et al. 2000). About 90% of the freshwater input to the bay comes from direct precipitation (average 98 cm year^{-1}). The remaining 10% is runoff from the Everglades, mostly from managed canal discharges (Nuttle et al. 2000). About 75% of annual precipitation occurs in the wet season (Schomer and Drew 1982), from May to October. Mean annual water temperature is 24.5°C. The lowest mean monthly temperature is 20°C in January and the highest mean monthly temperature is 28°C in August. Tropical storms and hurricanes regularly impact the bay, with a range of effects such as modification of geomorphology, sudden decreases in salinity, remobilization and redistribution of bottom sediments, destruction of vegetation cover, and changes in water nutrient concentrations.

Data Collection

A network of water quality monitoring stations was established by Florida International University (FIU) in Florida Bay beginning in 1989 (Fig. 1). Water column measurements and samples were collected every other month from July 1989 to December 1990 and then monthly from March 1991 to the present (Boyer and Briceño 2007). Monitoring included field measurements of surface and bottom salinity (practical salinity scale), temperature (°C), dissolved oxygen (DO, milligram per liter), and turbidity. Duplicate, unfiltered water samples were collected from 10 cm below the surface using sample rinsed 120-ml HDPE bottles and kept at ambient temperature in the dark during transport. Duplicate water samples for dissolved nutrient analysis were collected using sample rinsed 150-ml syringes. Water samples were filtered onto 25 mm 0.7 μm glass fiber filters (Whatman GF/F), which were placed in 2-ml plastic centrifuge tubes to which 1.5 ml of 90% acetone was added. Filters for CHLA were allowed to extract for a minimum of 2 days at −20°C before analysis. Extracts were analyzed using a Gilford Fluoro IV Spectrofluorometer (excitation=435 nm, emission=667 nm), and compared to a standard curve of pure chlorophyll *a* (Sigma) and reported in microgram per liter. Details of sampling methodology and laboratory analysis have been described elsewhere (Boyer et al. 1999; Boyer and Briceño 2007).

Data Handling

Factor Analysis and Clustering

Boyer et al. (1997) used water quality monitoring data from 1989–1996 to subdivide Florida Bay into three spatial zones having similar characteristics. They applied principal component analysis coupled with a *K*-means cluster analysis establishing "zones of similar influence" (ZSI). We reassessed their subdivisions using the data set extending to 2007, by applying factor analysis and hierarchical clustering. Only data points for which all parameters had been reported from March 1991 to December 2007, were included in the analyses; i.e. total organic carbon (TOC), total nitrogen (TN), total organic nitrogen (TON), total phosphorous (TP), chlorophyll *a* (CHLA), soluble reactive phosphorous (SRP), nitrite-N (NO_2^-), nitrate-N (NO_3^-), ammonium (NH_4^+), salinity, turbidity, temperature, and dissolved oxygen.

After applying factor analysis with VARIMAX rotation of axes (StatView®), we tried combinations of mean, standard deviation, variance, median, inter-quartile range (IQR), and median absolute deviation (MAD) of the scores for each sampling site as input for the cluster routines. We compared hierarchical and *K*-means clustering using Euclidean distance as metrics and either single linkage (nearest neighbor) or Ward minimum variance methods using SYSTAT®. After detailed analysis of results, given the consistency of the associations of sampling stations, their geographical distribution, and their geomorphologic setting, we adopted the hierarchical cluster analysis method to define clusters or ZSI. Input for the hierarchical cluster routine was two parametric indexes (means and standard deviation) and two non-parametric indexes (median and MAD).

To summarize descriptive statistics for each ZSI we used box-and-whisker plots, where the horizontal line at the

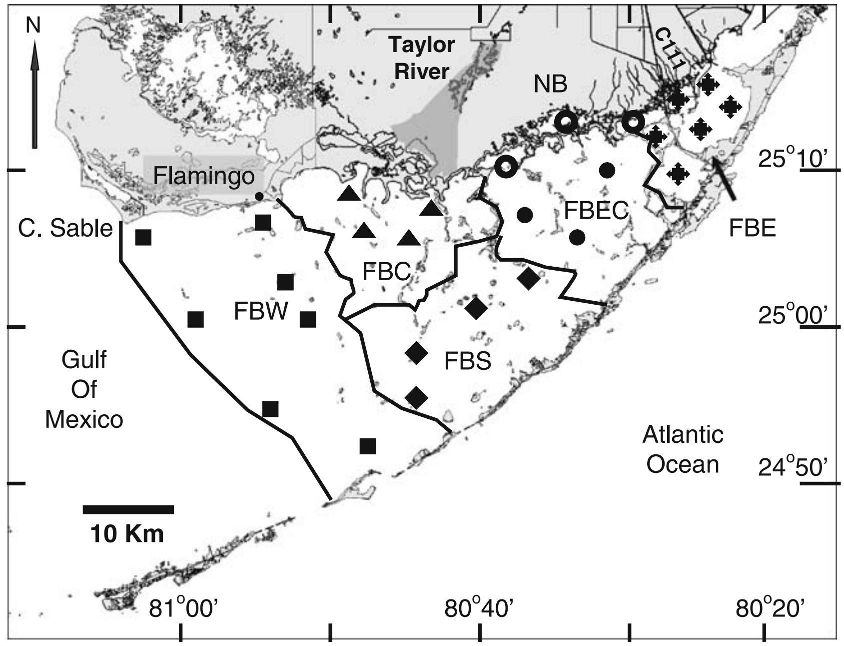

Fig. 1 Map of Florida Bay showing FIU monitoring network and factor analysis-clustering subdivision of Florida Bay into six zones: Florida Bay East (*FBE*; *stars*), Florida Bay East-Central (*FBEC*; *filled circles*), Northern Bays (*NB*; *open circles*), Florida Bay Central (*FBC*; *triangles*), Florida Bay South (*FBS*; *rhombs*), and Florida Bay West (*FBW*; *squares*). Base-map after Fourqurean and Robblee (1999)

center of the box is the median of the data and the notch covers the 95% confidence interval of the median. The top and bottom of the box are the first and third quartiles and the ends of the whiskers are the fifth and 95th percentiles. Non-parametric Mann–Whitney tests were used to compare biogeochemical variables among ZSI and also between wet and dry seasons.

Normalized Cumulative Sum Charts

After subdividing Florida Bay into ZSI, most of our work relied on the analysis and comparison of time series of data. In these data sets as in most time series of ecological variables, values are not normally distributed, have variable means, contain gaps, and potential regime shifts and incomplete cycles of diverse amplitude and wavelength. Hence, we explored the structure of the times series with simple but robust methods such as cumulative sum charts (Johnson 1961; Manly and MacKenzie 2000), before attempting to transform the time series. A cumulative sum (CUSUM) chart is a plot of the cumulative sum of deviations ($S_n=\Sigma[x_i-T]$ for $i=1\ldots.n$) from a target specification (T) against n, the sample number (Ewan 1963; Woodall and Adams 1993). For our analysis we used a variant of CUSUM, where original values (x_i) were replaced by their Z-scores ($z_i=(x_i-m)/s$ where m = mean and s = standard deviation), converting the series to a mean of zero and unit standard deviation before calculating the running sum (Taylor et al. 2002). CUSUM and Z-CUSUM produce similar charts and are well known in the field of industrial control (Ewan 1963; Duncan 1974; Grant and Leavenworth 1980). In practice, CUSUM is a low-pass filter (Manly and MacKenzie 2000) which removes high-frequency noise and smoothes the data. This direct and easy connection between CUSUM and process performance has resulted in increasing applications of these charts to the earth sciences, especially for the analysis of time series in oceanography, geology, and ecology (Ibanez et al. 1993; Briceño and Callejon 2000; Manly and MacKenzie 2000; Adrian et al. 2006; Molinero et al. 2008).

The advantage of Z-CUSUM diagrams over conventional CUSUM charts is that in the former, values are expressed as multiples of standard deviation, expediting transformation into original units. A segment with a positive slope in the Z-CUSUM line graph represents a period where the values in the series are above average. Similarly, segments with negative slopes indicate below-average values, while horizontal segments in the Z-CUSUM represent average conditions. A cup-shaped Z-CUSUM chart indicates an increasing trend, while a dome-shaped curve describes an overall declining trend. Once suspected shifts were identified in the Z-CUSUM charts, the original data set was analyzed for breaks (Change-point Analyzer®, Taylor 2000a). The procedure uses an iterative combination of CUSUM charts and bootstrapping to detect breaks in the slope (Hinkley 1971; Hinkley and Schechtman 1987) and provides both confidence levels and confidence intervals for each change. As the z-scores are standardized values, the plots enable direct comparison of the date of change for different variables, irrespective of their absolute values. Differences between the sub-periods before and after a significant shift in the cumulative z-score plots were independently tested for significance using the non-parametric Mann–Whitney test.

Results

Subdivision of Florida Bay by PC-Cluster Analysis

Our factor analysis yielded six main factors (F1 to F6; $p<0.05$) which explained 79.1% of the variance. Varimax rotation allowed direct linkage of these factors to specific water quality parameters as shown in Table 1. F1 was mostly a function of TN, TON, and TOC; F2 was mostly composed of inorganic N species, NO_2^-, NO_3^-, and NH_4^+; F3 main loadings were TP, CHLA, and turbidity; F4 principally included temperature and DO; F5 was highly correlated with SRP; and F6 was an exclusive function of salinity. There is a striking similarity between these factors and the principal components derived by Boyer et al. (1997) for Florida Bay, except that SRP now defines a new factor. This similarity in results suggests highly robust and long-lasting relationships among variables.

We calculated the mean, standard deviation, median, and median absolute deviation for the factor scores for each of the sampling sites, and used those statistics as input for the hierarchical clustering routine (SYSTAT®). Euclidean distances were the metrics and either single linkage (nearest neighbor) or Ward minimum variance methods were used to define clusters or ZSI. Preliminary results indicated that including sampling sites from small bays along the northern margin of FB biased the analysis leading to the formation of clusters whose samples were geographically dispersed. Hence, we excluded those samples from further cluster analysis and kept them as a separate group. Finally, we selected two parametric indexes (mean and standard deviation) and two non-parametric indexes (median and MAD) as input for hierarchical clustering, and Ward minimum variance to define clusters (Fig. 1). This selection rendered consistency in the associations of sampling stations, and coherence in their geographical distribution and geomorphologic setting, as compared to those obtained when using single linkage methods.

The combination of results from our factor analysis and clustering methods subdivide Florida Bay into five discrete zones (Fig. 1): Florida Bay East (FBE), Florida Bay East-Central (FBEC), Florida Bay Central (FBC), Florida Bay South (FBS), and Florida Bay West (FBW). Finally, we incorporated the Northern Bays (NB) as an additional group. As expected, the statistical subdivision obtained with combined factor analysis and clustering reflects two water-mixing gradients, east–west and north–south, between fresh water draining from the Everglades and either Gulf waters to the west or Atlantic waters to the south. These clusters mimic very closely the divisions of Florida Bay defined by benthic plant communities (Zieman et al. 1989; Fourqurean and Robblee 1999) and by phytoplankton communities (Phlips et al. 1999)

Zone Characteristics

Northern Bays

The NB includes three relatively isolated bays (Long Sound, Joe Bay, and Little Madeira Bay) in the northeast region of Florida Bay, which are not significantly affected by tidal water exchange with marine waters. Salinity and nutrient concentrations react quickly to rainfall and inflow from creeks draining Taylor Slough and C-111 canal (Cosby et al. 2008). During drought periods hypersalinity can develop with salinities up to 54. NB was relatively free of algal blooms with the lowest median CHLA concentration in Florida Bay (median=0.64 µg l^{-1}; Table 2). Low incidence of blooms is the result of extreme P limitation resulting from low P contributions from the Everglades and Ca-rich sediments that immobilize P (Boyer et al. 1997; Fourqurean and Robblee 1999). Climate trends of CHLA

Table 1 Loading resulting from factor analysis for Florida Bay water samples

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
NO3	−0.131	0.550	0.031	0.080	0.012	−0.476
NO2	−0.035	0.836	3.809E-4	−2.280E-5	−0.015	−1.496E-4
NH4	0.178	0.775	−0.106	−0.009	0.021	0.158
TN	0.863	0.192	−0.021	0.017	−0.024	0.053
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
SRP	4.301E-4	0.009	0.010	0.009	0.956	−0.028
CHLA	0.128	−0.200	0.698	−0.029	−0.021	−0.002
TOC	0.784	−0.055	0.009	0.028	0.031	−0.113
SAL_S	−0.076	0.081	0.025	0.090	−0.031	0.843
TEMP_S	0.100	−0.087	−0.122	0.868	−0.038	−0.132
DO_S	0.045	−0.122	−0.017	−0.814	−0.041	−0.166
TURB	−0.192	0.197	0.783	−0.041	−0.111	−0.089

These six factors explain 79.1% of the data variance

Table 2 Parametric and non-parametric statistics for CHLA in each ZSI

	Florida Bay	NB	FBE	FBEC	FBC	FBS	FBW
Mean	1.35	0.84	0.85	0.51	2.75	0.99	1.98
SD	1.86	0.72	1.15	0.42	3.11	1.20	2.04
Minimum	BD	0.02	BD	0.04	0.11	0.07	0.06
Maximum	35.61	6.22	10.02	2.93	35.61	11.35	22.08
Variance	3.46	0.52	1.31	0.18	9.65	1.44	4.17
Median	0.74	0.64	0.49	0.33	1.53	0.54	1.30
IQR	1.07	0.65	0.60	0.56	3.27	0.83	1.90
MAD	0.44	0.30	0.26	0.16	1.03	0.31	0.79

BD below detection limit <0.001 mg l^{-1}

(Fig. 3) and the results of Mann–Whitney tests indicate that CHLA in NB is lower in the wet season (May–October) than in the dry season ($p<0.005$). Results also suggest that CHLA distribution is bimodal during the dry season, with one peak occurring in November–December and a second one in March.

Eastern Florida Bay

FBE, located at the extreme northeast portion of FB (Fig. 1), is mostly unaffected by tides or the direct influence of marine waters, due to the damping effect of mud banks to the west and the Florida Keys to the south. Most interaction is with NB to the north and FBEC to the west, so residence times are long. The major contribution to its freshwater budget comes from rain and mixing with NB. CHLA was very low (median=0.49 μg l^{-1}) in FBE. Concentrations were significantly higher in the wet season (median=0.56 μg l^{-1}) than in the dry season (0.39 μg l^{-1}), but the range was greater during the latter (Fig. 2). Phytoplankton blooms were practically absent in FBE until 2005, when an extensive cyanobacterial bloom developed, putatively in response to the impact of a major hurricane (Rudnick et al. 2006, 2007). The phytoplankton communities in the eastern bay are principally composed of centric diatoms (e.g., *Thalassiosira* sp.), dinoflagellates (e.g., *Protoperidium* spp., *Ceratium* sp., and *Prorocentrum micans*), and small cyanobacteria making the major fraction of cellular biovolume (Phlips and Badylak 1996; Hunt and Nuttle 2007). Steidinger et al. (2001) observed temporal shifts in phytoplankton community structure in eastern FB from a dominance of dinoflagellates from the fall 1994 to early summer 1995, to cyanobacteria from late 1996 to spring 1997.

East Central Florida Bay

FBEC is located north of Key Largo (Fig. 1) between 80º 30’ and 80º 40’ west latitude. Freshwater from the Everglades is supplied by Taylor River, Mud Creek, East Creek, and most prominently Trout Creek (up to 32 m^3 s^{-1}) along its northern boundary. CHLA (median=0.33 μg l^{-1}) was the lowest in Florida Bay especially during the wet season (Table 2; Fig. 3). Its median TN:TP ratio of 99.7 was the highest bay wide, confirming the strong P limitation for seston previously reported for this portion of FB (Boyer et al. 1997; Fourqurean and Robblee 1999). FBEC covers the same area as the “East Zone” of phytoplankton communities described by Phlips et al. (1999), who observed *Synechococcus* biovolumes of less than 1.0×10^5 μm^3 ml^{-1} from August 1993 to October 1997. Their analyses indicate that phytoplankton assemblage in FBEC is made up of cyanobacteria, dinoflagellates, diatoms, and microflagellates in different proportions with cyanobacteria as the minor component. According to Hunt and Nuttle (2007) and Hitchcock et al. (2007) this area had been practically bloom-free for the period 1988–2003, with a maximum CHLA concentration of 5 μg l^{-1} (Phlips and Badylak 1996; Boyer et al. 1999)

Central Florida Bay

FBC is located in the north central portion of Florida Bay (Fig. 1), FBC is an isolated basin with scarce freshwater runoff from the Everglades, mostly supplied by McCormick Creek and Alligator Creek, resulting in an internal north–south salinity gradient. Timing and volumes of precipitation and runoff play a significant role on conditions in FBC, where hypersalinity occurs periodically, with salinities up to 70 due to high evaporation (Boyer 2004; Robblee et al. 1991). FBC had the highest nutrient concentrations in the bay and the widest nutrient concentration range. Median TN:TP ratio was 53, intermediate between FBEC (99) and FBW (24). Median CHLA concentrations (1.53 μg l^{-1}) were also highest at FBC and bloom events were common with concentrations up to 35.5 μg l^{-1}. Maximum bloom activity was from July to January (Fig. 3). The reported P limitation in FBEC to the east (TN:TP=99 and DIN:SRP=78) and N limitation in FBW to the west (TN:TP=24 and DIN:SRP=11), places FBC in a special location, nutrient ratios regularly approach Redfield values, possibly enhancing algal bio-

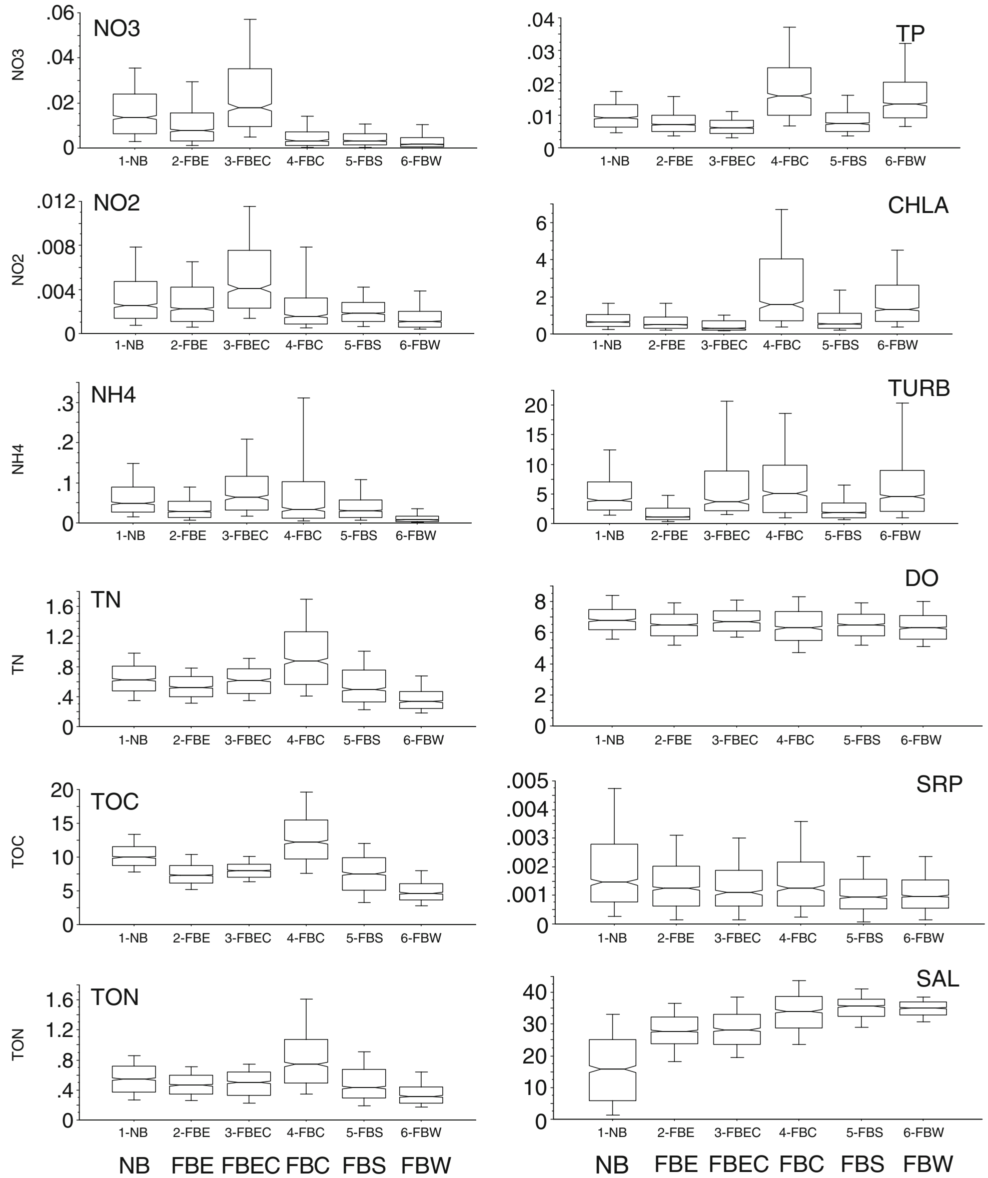

Fig. 2 *Box-and-whisker plots* for defined zones in FB and variables which dominate each component (F1 to F6) of the factor analysis. Units are milligram per liter, except CHLA (microgram per liter), turbidity (NSU), and salinity (PSU). Abbreviations as in Fig. 1

mass potential (Fourqurean et al. 1993; Fourqurean and Robblee 1999; Hitchcock et al. 2007)

FBC coincides with the "North Central" zone of phytoplankton communities of Phlips et al. (1999), where the picoplanktonic cyanobacterium *Synechococcus* cf. *elongatus*, was the dominant bloom forming algae with biovolume levels exceeding 1.0×10^{7} μm^{3} ml^{-1}. Other cyanobacteria, diatoms, and dinoflagellates typically took on secondary roles during bloom events. Nevertheless, Tomas et al. (1999) indicated that diatoms are periodically a major component, especially in Rankin Lake, where addition of silica stimulates productivity. The persistence of blooms in FBC may well be a consequence of the described characteristics and location of this zone, but according to Phlips et al. (1999) is also due to the special ecophysiological characteristics of the *Synechococcus* cf. *elongatus*. Among them, its tolerance to a wide salinity range (5–50; Phlips and Badylak 1996), ability to compete for P at low concentrations, as underscored by the high alkaline phosphatase activity levels (median APA= 1.14 μM h^{-1}); capacity to regulate buoyancy, ability to take up organic N, and resistance to grazing losses (Hitchcock et al. 2007)

Southern Florida Bay

FBS occupies the south central portion of FB, coinciding with the "South Central" zone of phytoplankton communities described by Phlips et al. (1999). Besides rainfall contributions, FBS waters are affected by water inflows from FBC and exchange with the Atlantic Ocean through

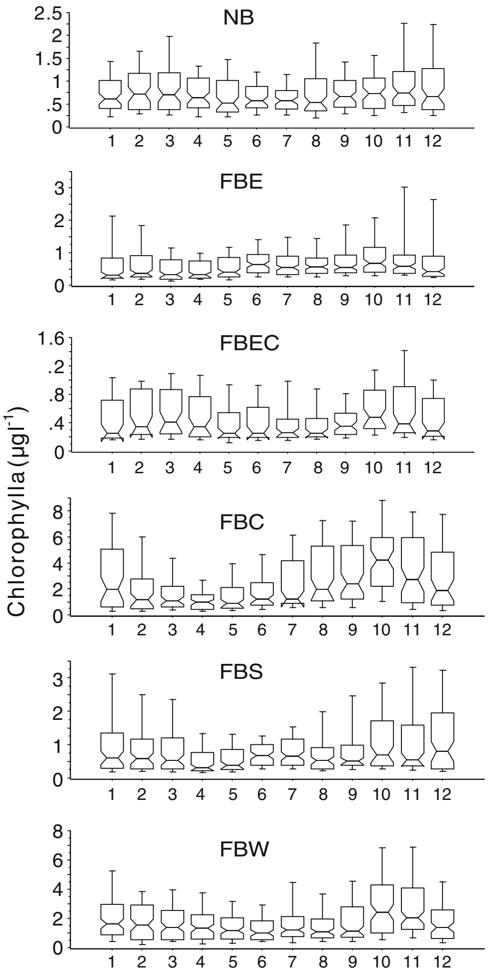

Fig. 3 Climatology of CHLA in the ZSIs in Florida Bay. Abbreviations as in Fig. 1

passes in the Florida Keys. Median TN:TP ratio was 77 suggesting P limitation for seston production. Median CHLA concentration was moderate (0.54 μg l^{-1}) with maximum values in the dry season (Fig. 3). Studies of phytoplankton biomass (Phlips et al. 1999) indicate that phytoplankton assemblages are typically dominated by *Synechococcus* cf. *elongatus*, with blooms occurring from October to January as a consequence of wind-driven movement of phytoplankton-rich waters south from FBC (Hitchcock et al. 2007)

Western Florida Bay

FBW extends over the highly dynamic western extreme of FB with a boundary open to the Gulf of Mexico, but isolated from direct overland freshwater sources. Tidal effects are strong in FBW (Wang et al. 1994) and causes short residence time and salinities close to marine levels. Median TN:TP ratio was 25, slightly above Redfield ratio, but not suggestive of major N limitation. Median CHLA concentration (1.30 μg l^{-1}) was relatively high. Contrasting with the rest of Florida Bay, blooms in FBW are dominated by diatoms and mainly composed of *Rhizosolenia* spp., and subdued proportions of *Chaetoceros* spp. and resuspended pennates from the bottom (Hitchcock et al. 2007). These blooms seem to develop on the shelf responding to high flows from the Shark River, to be advected into the bay around Cape Sable (Tomas et al. 1999; Phlips et al. 1999; Hitchcock et al. 2007). CHLA climatology (Fig. 3) suggests a bimodal distribution for blooms with a mode in October–November and a second one in January.

Exogenous Drivers

Potential external climatic drivers were explored for the 40 years data set to identify shifts or trends, which may help to explain observed changes in water quality and phytoplankton biomass. The focus was on the North Atlantic oscillation, the Atlantic multidecadal oscillation index and tropical cyclone activity, as they relate to regional and local phenomena, such as precipitation over the bay, managed flows into the bay from the Everglades, and hurricane impacts. With that objective, we explored the structure of time series using Z-CUSUM charts, which provided direct visual comparison among time series.

The NAO time series from 1970 to 2008 was downloaded directly from the National Oceanographic and Atmospheric Administration (NOAA) Climate Prediction Center webpage (http://www.cpc.ncep.noaa.gov), and the Z-CUSUM was constructed without any prior data treatment. The results show substantial interseasonal and interannual variability during the negative phase of the NAO, which prevailed from the mid-1950s to early 1979 (Hurrell 1995). The Z-CUSUM chart shows a below-average rainfall period from 1970 to mid-1982 (Fig. 4). In mid-1982 NAO values shifted towards above-average values with two cycles of about 3.5 years each. In 1989 a highly positive NAO phase began (steep positive slope), which persisted until mid-1995. A return to strong negative phases began in late 1995, which persisted until August 2008 with some abrupt oscillations. Strong positive NAO phases (positive slopes) result in warmer temperatures and higher precipitation in southeastern United States, with negative phases producing the opposite result (Hurrell 1995). Statistically significant change-points were detected in December 1988, April 1995, and April 2008 with 93%, 100%, and 91% confidence levels (CL), respectively. The sharp break in 1995 is associated with a multidecadal change from cool–dry to warm–wet conditions.

The Atlantic multidecadal oscillation, which expresses the variability of the North Atlantic sea surface temperature (SST) field (Kerr 2000), is a major climate driver over the Atlantic tropical region (Delworth and Mann 2000), with

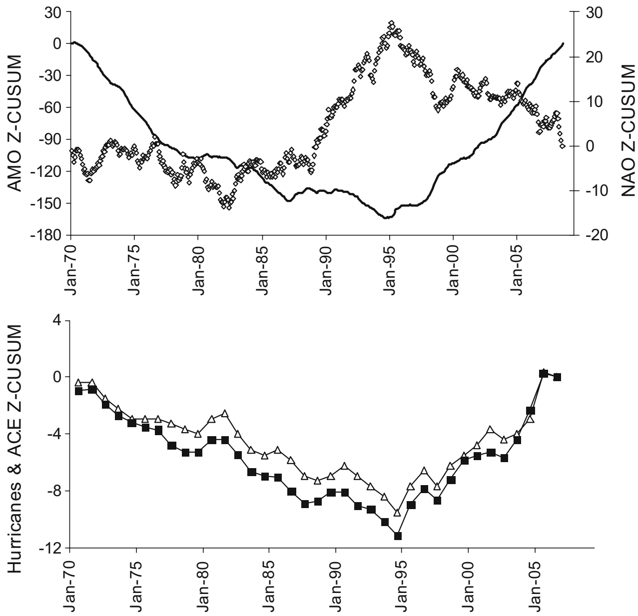

Fig. 4 Z-CUSUM charts for North Atlantic Oscillation (*NAO*; *open rhombs*) and the Atlantic Multidecadal Oscillation (*AMO*; *black thin line*) indexes; number of North Atlantic hurricanes (*open triangles*) and Accumulated Cyclone Energy (*ACE*; *filled squares*). A segment with a positive slope in the Z-CUSUM line graph represents a period where the values in the series are above average. Similarly, *segments with negative slopes* indicate below-average values, while *horizontal segments* represent average conditions. A *cup-shaped* Z-CUSUM chart indicates a secular increasing trend, while a *dome-shaped curve* describes an overall declining trend. Note the positive correlation among AMO, hurricanes and ACE, and the negative relationship with NAO. Common to all these drivers is a strong shift at the end of 1994

cool–dry and warm–wet conditions linked to negative and positive AMO phases, respectively The AMO data set was downloaded directly from NOAA's Earth System Research Laboratory webpage (http://www.cpc.ncep.noaa.gov). An AMO cool/dry phase for the North Atlantic basin was in effect from 1970 to 1990 (Kerr 2000; Enfield et al. 2001), and has been increasing since then. The Z-CUSUM for the AMO time series displayed the opposite of the NAO (Fig. 4), but shared a common and drastic change in late 1994 (confidence limit=96%), suggesting a shift to higher SST and higher precipitation rates.

In keeping with the aforementioned trends, the period from 1970 to 1994 had low tropical cyclone activity, in terms of number, frequency, and strength of hurricanes (Category ≥3 in the Saffir-Sympson scale; Landsea et al. 1996; Goldenberg et al. 2001). By contrast, 1995–2005 was a period of high cyclone activity and precipitation rate. Figure 4 also shows the Z-CUSUM charts for number of hurricanes and the accumulated cyclone energy for the period 1970–2006. The ACE is an index that combines the number of storm systems, their duration, and intensity. These multi-decadal scale fluctuations in hurricane activity and ACE are related to fluctuations in SST (Goldenberg et al. 2001) and have a positive correlation with AMO.

Endogenous Drivers

Rainfall data for Florida Bay are from meteorological stations located at the Florida Coastal Everglades LTER, Key West, and Flamingo (Fig. 1). Time series were obtained from the South Florida Water Management District DBHYDRO database, and the average monthly precipitation was calculated for each station, from which cumulative curves were constructed. The data sets had similar Z-CUSUM patterns and displayed high seasonal variability, and cycles of variable spans and amplitudes. We explored the consistency of these patterns in the region, which shared similar trends for sites north of Florida Bay, including Tamiami, Miami Airport, and West Palm Beach stations. Hence, we used the Everglades LTER station as representative of rainfall in the overall study area. From 1970 to May 1990, precipitation was generally below average, except for a short increase in 1982–1984 (Fig. 5). Besides seasonality, there were some short 4–6 year cycles present. From mid 1990 to April 1995 precipitation was slightly above average; and since May 1995 to October 2003 precipitation was well above average, with an apparent decline after 2003. The rainfall time series has several data gaps and is affected by seasonality and autocorrelation, so it was linearly interpolated and corrected for seasonality before performing change-point tests. The most significant changes occurred in January 1991 (100%

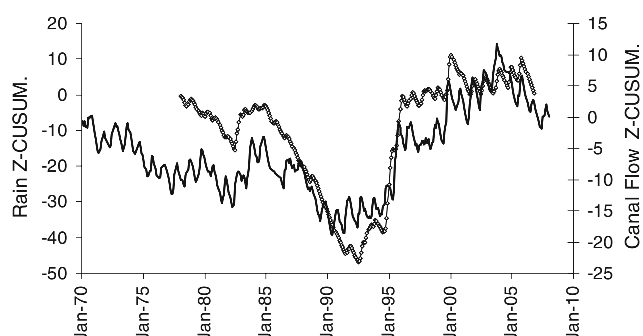

Fig. 5 Z-CUSUM chart for rainfall data (*thin line*) at the Everglades station and managed water flows (*thick line*) into Everglades National Park from the Tamiami Canal (SFWMD Structures S12-A, B, C and D; DBHYDRO). Main components of the rainfall time-series structure are: (1) a generalized increasing secular trend (note *cup-shaped curve*) characterized by below-average precipitation rate extending from 1970 to 1990 and above-average rainfall from 1991 to 2004; (2) ill-defined 4–5 year cycles; and (3) seasonality. Water flow follows precipitation with a generalized below-average tendency until mid-1992, followed high flow levels until early-1996, and finally, slightly above-average tendency until 2006

CL), November 1997 (99% CL), and January 2004 (86% CL).

Freshwater flow volumes delivered by the South Florida Management District (SFWMD) to the Shark River Slough in the Everglades National Park, which are ultimately conveyed into Florida Bay, are closely tied to precipitation rates (Fig. 5). The flow volume signal mimics that of precipitation, except for events of extremely high flows delivered during major storms, which cause sudden drops in salinity and nutrient load unbalance. The latter event can cause major disturbances in the bay. Additional information to substantiate shift in the ecology of Florida Bay in the early 1990s, comes from stage and flow measurements from 1978 to 1999 in the Taylor River Basin (station NP-TSB; latitude 252406, longitude 803624; DBHYDRO), which shows a substantial shift from below average to above-average level, for both stage and flow, centered around 1992–1994. In summary, the major signal shifts of global climatic stressors (NAO, AMO) seem to be imprinted on precipitation and water flow to Florida Bay, (rain plus canal inflows). On one hand, water management has a limited effect on freshwater flows to the bay; however, the difference it can make in the water budget of Florida Bay is large, especially during seasonal extremes.

Climate and Phytoplankton Biomass

Tropical storms and hurricanes regularly impact the bay and modify its geomorphology, and hence, its circulation and salinity patterns. Nutrient concentrations can change suddenly as sediments are resuspended and redistributed, and the destruction of sub-aquatic vegetation increase erosion and redistribution of bottom sediments. The conditions imposed by hurricanes drive significant responses from phytoplankton, as reflected by changes in CHLA in the water column.

A common feature of all zones of the bay was the dome-shaped pattern of the CHLA Z-CUSUM charts (Fig. 6), indicating a generalized decline in CHLA across the bay, at least until 2005. Vertical dashed lines in Fig. 6 indicate the approximate location of the major regime shift (SS) in global drivers and precipitation rate discussed above, and also the occurrence of hurricanes during the monitoring period. This shift was centered around 1994–1995. As observed, hurricane events were correlated to sudden increases in CHLA. Regime system shifts (SS) are best displayed in FBE and FBEC by drastic decreases in CHLA concentration, 57% and 70%, respectively. A smaller decline was observed in FBC (26%) in 1994 and a stronger one in 1995 (46%). In FBS the shift occurred in March–April 1995, with a 60% decline in CHLA. In NB the regime shift was more difficult to define, but it seems to occur in late 1993, preceding the changes in other regions and

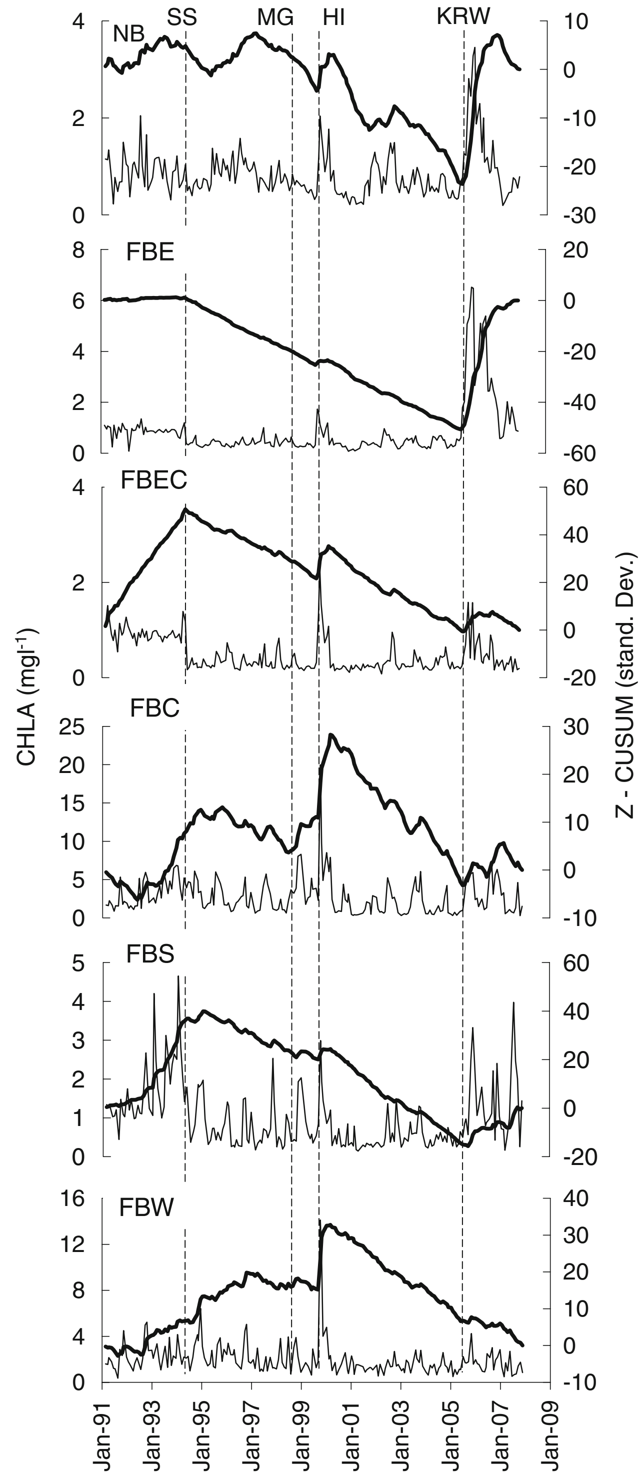

Fig. 6 CHLA concentration and Z-CUSUM charts for zones in Florida Bay. *Vertical lines* indicate: *SS* climate shift identified in NAO, AMO, ACE, North Atlantic storm activity and precipitation; *MG* Hurricanes Mitch and Georges; *HI* Tropical storm Harvey and Hurricane Irene; *KRW* Hurricanes Katrina, Rita, and Wilma

coupling more closely with the shift in SST towards a positive phase on the summer of 1994 (Enfield et al. 2001). Major shifts were not observed in FBW.

Hurricanes Mitch (M) and Georges (G) impacted Florida Bay in 1998, with corresponding increases in CHLA levels in FBC, FBW, and FBS (Fig. 6). Before the ecosystem recovered from the 1998 disturbance the bay was hit again by tropical storm Harvey (H) and Hurricane Irene (I) in 1999, with major impacts to the central and western portions of Florida Bay. Harvey and Irene were associated with the largest and most sustained blooms in the record for the central and western portions of Florida Bay (Boyer and Briceño 2007). In NB and FBEC the impact on CHLA was relatively small, while in FBE it was minor. The disturbance caused by hurricanes Katrina, Rita, and Wilma in the summer/fall of 2005 were associated with the largest recorded increases in CHLA concentrations for NB and FBE, areas traditionally known for very low CHLA levels (Figs. 2 and 6). In FBEC, FBC, FBS, and FBW the impacts of the three storms on CHLA levels were relatively minor.

Discussion

Changes of water quality in Florida Bay during the late 1980s including increases in the frequency and magnitude of phytoplankton blooms and the onset of massive seagrass die-offs have been blamed on salinity increases due to reduced freshwater delivery from the Everglades (Robblee et al. 1991; Fourqurean et al. 2003; Hunt and Nuttle 2007). Responsibility has also been laid to anomalous pulses of freshwater from the Everglades imposed by water management on schedules departing from natural cycles (Brand 2001). The lack of pre-seagrass die-off information hinders the definitive allocation of causes and/or responsibilities. For the current study period (1989–2007) we attempted to establish a link between potential drivers and ecosystem response, in an effort to explain those changes occurring in water quality on a regional specific basis.

Florida Bay is physically compartmentalized and our results indicate that it may be subdivided into six zones where not only water quality, circulation patterns, biotic communities are distinct (Hunt and Nuttle 2007), but also the responses to meteorological, hydrological, and climatic stressors are different between zones. Our analyses were performed in a space–time framework by studying the evolution of stressors and their variability, in terms of CHLA as the indicator of phytoplankton biomass.

Strong positive NAO phases are associated with warmer temperatures and higher precipitation rate in the eastern United States, while negative phases produce dryer conditions (Hurrell 1995). Following a highly variable period from 1970 to 1988 (Fig. 4), statistically significant change-points were detected in the NAO time series during December 1988 (93% CL), April 1995 (100% CL), and April 2008 (91% CL). These resulted in lower precipitation during 1988–1995 and increasing rain for 1995–2008. On the other hand, the Atlantic multidecadal oscillation which expresses the variability of the North Atlantic sea surface temperature field (Kerr 2000) is considered a major climate driver over the tropical Atlantic region (Delworth and Mann 2000). The effects of AMO on rainfall have been specifically demonstrated for central and south Florida (Enfield et al. 2001), where rainfall is positively correlated to AMO. Hence, dry periods correspond to AMO cool phases (negative slopes in AMO Z-CUSUM, Fig. 4), and rainfall is more copious when the Atlantic is in AMO's warm phases (positive slopes in AMO Z-CUSUM, Fig. 4). AMO and NAO time series experienced drastic shifts in June 1994 and April 1995, respectively, reinforcing their individuality as drivers in system shift. In summary, globally linked indexes (NAO, AMO, ACE) and hurricane development have all relate well to regime shifts in 1994–1995. Additionally, the clear shift from prevailing negative to positive phases of NAO in the late 1980s (91% CL) is also evident in our data (Fig. 4).

The results of our analysis indicate a causal link between CHLA and meteorological, hydrological, and ecological patterns, which in turn are related to NAO, AMO, and ACE and storm frequency. Similar proxies using, CUSUM methodologies, have been proposed for phenological changes in copepod communities in the Ligurean Sea (Molinero et al. 2008) and for phenological changes in Lake Mügeelsee, Germany (Adrian et al. 2006). A drastic drop in CHLA concentration occurred in the summer of 1994 (Fig. 6), especially in FBE, FBEC, and NB. Since 1994, the common time series feature has been a lower baseline and greater amplitude of departures from the median. Except for the departures, this pattern closely follows those observed for NAO, AMO, ACE, and hurricane frequency. The decadal or multidecadal cycles associated with these indexes also correspond to cycles in Atlantic atmospheric circulation and SST. Hence, we interpret this sudden decline in CHLA as the ecosystem response to the regime shifts in global drivers (NAO, AMO, ACE) and local drivers (precipitation and storms) centered around 1994.

Spatial differences in the magnitude of disturbance (amplitude of deviation in Z-CUSUM charts, Fig. 6) caused by the combined impact of tropical storms Harvey and Hurricane Irene (higher on FBC, FBS, and FBW), as compared to Katrina, Rita, and Wilma (higher on NB and FBE), may be explained by differences in their tracks and precipitation totals. Terrestrial runoff from tropical storm Harvey and Hurricane Irene was responsible for 60% of the annual freshwater input to FB within a 4-week period and supplied 65% of the annual TN and TP loads (Davis et al. 2004; Williams et al. 2008). Taylor Slough (just upstream from FBC) and the Shark Slough experienced a twofold increase in NH_4^+ and SRP concentrations. Shark River outflow created a plume in the Gulf of Mexico which circulated around Cape Sable, finally entering FBW and FBS in Florida Bay (Hitchcock et al. 2007), fueling a major phytoplankton bloom. The effects of runoff events in 1999 were also felt in eastern FB, but the magnitude was smaller.

The impact of Hurricanes Katrina, Rita, and Wilma in 2005 was concentrated in eastern Florida Bay with resulting algal blooms. Rudnick et al. (2007) hypothesized that these blooms were the system response to both natural and anthropogenic drivers, which unfortunately coincided in space and time. Previous to Katrina, construction work associated with the widening of US Highway 1 included mangrove forest clearing, in situ mulching, and mixing with soil, all of which increased TP load to the adjacent waters. Additionally, canal discharges were increased considerably as a flood control measure to mitigate Katrina impacts. Combined water input from discharge and Katrina increased to over 30 million m^3 in August. The sudden freshening caused massive SAV die-off and generation of detritus, which combined with benthic flux from sediment resuspension produced by hurricane winds, and increased TP and TOC concentrations triggered (September) cyanobacterial blooms which expanded spatially into November 2005 (Rudnick et al. 2007). Since then, the bloom has been sustained by the long water residence time in the basin and further SAV mortality through April 2008.

The disparities in the responses of Florida Bay (i.e. CHLA) to different hurricanes is apparently related to specific tracks, magnitudes of the events (i.e. precipitation, wind strength), and environmental conditions before and after the events (Williams et al. 2008). Hurricane Irene made landfall on western Florida Bay and was associated with record precipitation (over 60 mm). Previous to Katrina, elevated discharge from canals was conveyed to FBE, where an additional source of nutrients was available from road construction and has remained as such after the impacts of KRW. We believe that these added anthropogenic impacts in NB and especially in FBE, not present in the central and western portions of FB, are the final cause of the extended bloom that still persists in FBE.

Our results indicate that water quality in Florida Bay is steadily responding to decadal or multidecadal forcing factors that dictate baseline conditions. Superimposed on that baseline are seasonal cycles and departures from "normality" caused by short-lived events (i.e. hurricanes). The behavior of CHLA, salinity, and total nutrients (TN, TP, and TOC) seem to closely follow that model. Furthermore, conflicting hypotheses as to the cause of ecological degradation of Florida Bay since the late 1980s (i.e. seagrass die-off and bloom persistence), attributed to high salinity from low Everglades water supply (Robblee et al. 1991; Fourqurean et al. 2003; Hunt and Nuttle 2007) and lower salinity and increased nutrient supply from the Everglades (Brand 2001), may be reconciled under the perspective of this model.

Perhaps the die-offs occurred when Florida Bay experienced high salinities and elevated nutrient concentrations during the 1980s from reduced Everglades water deliveries (natural and anthropogenic) as a result of reduced rainfall forced by NAO and AMO. Furthermore, seagrass recovery since 1995 (Fourqurean et al. 2003) coincides with the beginning of higher precipitation rates associated to AMO and NAO phases and parallels higher freshwater deliveries to the bay.

Return to pre-disturbance conditions after hurricane impact is generally within 1 year, suggesting some degree of resilience to ecosystem disturbance. The exception is FBE where blooms, high TP concentrations, and generalized ecosystem deterioration (blooms, hypoxia, SAV mortality, and sponge die-offs) still persist more than 3 years after KRW impacts. Conditions in FBE underscore the consequences of breaching ecological thresholds and the following cascade of undesired results, something to keep in mind, when substantial efforts and resources are being devoted to restoration of the Everglades and Florida Bay.

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References

Adrian, R., S. Wilhem, and D. Gerten. 2006. Life-history traits of lake plankton species may govern their phenological response to climate warming. *Global Change Biology* 12: 652–661.

Belgrano, A., M. Lima, and N.C. Stenseth. 2004. Non-linear dynamics in marine phytoplankton population systems. *Marine Ecology Progress Series* 273: 281–289.

Box, G., G. Jenkins, and G. Reinsel. 1994. *Time-series analysis: Forecasting & control*. New Jersey: Prentice Hall.

Boyer, J.N., and H.O. Briceño. 2007. South Florida Coastal Water Quality Monitoring Network. FY2006 Cumulative Report South Florida Water Management District, Southeast Environmental Research Center, Florida International University (http://serc.fiu.edu/wqmnetwork/).

Boyer, J.N., J.W. Fourqurean, and R.D. Jones. 1997. Spatial characterization of water quality in Florida Bay and Whitewater

Bay by principal component and cluster analyses: Zones of similar influence (ZSI). *Estuaries* 20: 743–758.

Boyer, J.N., J.W. Fourqurean, and R.D. Jones. 1999. Seasonal and long-term trends in water quality of Florida Bay (1989–97). *Estuaries* 22: 417–430.

Brand, L. 2001. The transport of terrestrial nutrients to South Florida coastal waters. In *The Everglades, Florida Bay, and Coral Reefs of the Florida Keys*, ed. J.W. Porter and K.G. Porter, 361–414. Boca Raton: CRC.

Chatfield, C. 1996. *The analysis of time-series*, 5th ed. London: Chapman & Hall.

Cosby, B., W. Nuttle, and F. Marshall. 2005. FATHOM enhancements and implementation to support development of minimum flows and levels for Florida Bay. South Florida Water Management District Contract C-C-15975-WO05-05 Final Report. Environmental Consulting & Technology, Inc. 168 p.

Davis, S.E., J.E. Cable, D.L. Childers, C. Coronado-Molina, J.W. Day, C. Hittle, C.J. Madden, E. Reyes, D.T. Rudnick, and F.H. Sklar. 2004. Importance of storm events in controlling ecosystem structure and function in a Florida Gulf coast estuary. *Journal of Coastal Research* 20: 1180–1208.

Delworth, T.L. and M.E. Mann. 2000. Observed and simulated multidecadal variability in the Northern Hemisphere. *Climate Dynamics* 16: 661–676.

Duncan, A.J. 1974. *Quality control and industrial statistics*. Homewood: Richard D. Irwin.

Emery, W.J. and R.E. Thomson. 2001. *Data analysis methods in physical oceanography*, 2nd ed. San Diego: Elsevier.

Enfield, D.B., A.M. Mestas-Nuñez, and P.J. Trimble. 2001. The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental U.S. *Geophysical Research Letters* 10(28): 2077–2080.

Ewan, W.D. 1963. When and how to use Cu-sum charts. *Technometrics* 5: 1–32.

Fourqurean, J.W. and M. Robblee. 1999. Florida Bay: a history of recent ecological changes. *Estuaries* 22: 345–357.

Fourqurean, J.W., R.D. Jones, and J.C. Zieman. 1993. Processes influencing water column nutrient characteristics and phosphorus limitation of phytoplankton biomass in Florida Bay, FL, USA: Inferences from spatial distributions. *Estuarine, Coastal and Shelf Science* 36: 295–314.

Fourqurean, J.W., J.N. Boyer, M.J. Durako, L.N. Hefty, and B.J. Peterson. 2003. Forecasting responses of seagrass distributions to changing water quality using monitoring data. *Ecological Applications* 13: 474–489.

Goldenberg, S., C.W. Landsea, A.M. Mestas-Nunez, and W.M. Gray. 2001. The recent increase in Atlantic hurricane activity: Causes and implications. *Science* 293: 474–479.

Grant, E.L. and R.S. Leavenworth. 1980. *Statistical quality control*, 5th ed. New York: McGraw-Hill.

Hinkley, D.V. 1971. Inference about the change-point from cumulative sum tests. *Biometrika* 5: 509–523.

Hinkley, D. and E. Schechtman. 1987. Conditional bootstrap methods in the mean-shift model. *Biometrika* 74: 85–93.

Hitchcock, G.E. Phlips, E.J., Brand, L., Morrison, D., 2007. Plankton Blooms. In: Hunt, J.H., Nuttle, W. (Eds.), Florida Bay Science Program: A Synthesis of Research on Florida Bay. Fish and Wildlife Research Institute Technical Report TR-1

Hunt, J.H. and W. Nuttle. 2007. Florida Bay Science Program: A Synthesis of Research on Florida Bay. Fish and Wildlife Research Institute Technical Report TR-11.

Hurrell, J.W. 1995. Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation. *Science* 269: 676–679.

Ibanez, F., J.M. Fromentin, and J. Castel. 1993. Application of the cumulated function to the processing of chronological data in oceanography. *Comptes rendus de l'Acade´mie des Sciences, Serie* 3(318): 745–748.

Johnson, N.L. 1961. A simple theoretical approach to cumulative sum control charts. *Journal of the American Statistical Association* 56: 83–92.

Kerr, R.A. 2000. A North Atlantic climate pacemaker for the centuries. *Science* 288: 1984–1986.

Landsea, C.W., N. Nicholls, W.M. Gray, and L.A. Avila. 1996. Downward trends in the frequency of intense Atlantic hurricanes during the past five decades. *Geophysical Research Letters* 23: 1697–1700.

Manly, B.F.J. and D. MacKenzie. 2000. A cumulative sum type of method for environmental monitoring. *Environmetrics* 11: 151–166.

Manson, R. and D. Lind. 1996. *Statistical techniques in business and economics*, 9th ed. New York: Irwin-McGraw-Hill.

Molinero, J.C., F. Ibanez, S. Souissi, E. Buecher, S. Dallot, and P. Nival. 2008. Climate control on the long-term anomalous changes of zooplankton communities in the Northwestern Mediterranean. *Global Change Biology* 14: 11–26.

Nuttle, W., J.W. Fourqurean, B.J. Cosby, J. Zieman, and M. Robblee. 2000. Influence of net freshwater supply on salinity in Florida Bay. *Water Resources Research* 36: 1805–1822.

Phlips, E.J. and S. Badylak. 1996. Spatial distribution and composition of algal blooms in Florida Bay. *Bulletin Marine Science* 58 (1): 203–216.

Phlips, E.J., S. Badylak, and T. Lynch. 1999. Blooms of the picoplanktonic cyanobacterium *Synechococcus* in Florida Bay, a subtropical inner-shelf lagoon. *Limnology and Oceanography* 44: 1166–1175.

Robblee, M.B., T.B. Barber, P.R. Carlson Jr., M.J. Durako, J.W. Fourqurean, L.M. Muehlstein, D. Porter, L.A. Yarbro, R.T. Zieman, and J.C. Zieman. 1991. Mass mortality of the tropical seagrass *Thalassia testudinum* in Florida Bay (U.S.A). *Marine Ecology Progress Series* 71: 297–299.

Rudnick, D., C. Madden, S. Kelley, R. Bennett, and K. Cunniff. 2006. *Report on algae Blooms in Eastern Florida Bay and Southern Biscayne Bay.* Report: SFWMD Tech.

Schomer, N.S., and R.D. Drew. 1982. An ecological characterization of the lower Everglades, Florida Bay and the Florida Keys. FWS/OBS-82/58.1. US Fish and Wildlife Service, Office of Biological Services, Washington, D. C.

Steele, J.H. and E.W. Henderson. 1981. A simple plankton model. *American Naturalist* 117: 676–691.

Sturges, W. 1983. On interpolating gappy records for time-series analysis. *Journal of Geophysical Research* 88: 9736–9740.

Taylor, W. (2000a). Change-Point Analyzer 2.0 shareware program, Taylor Enterprises, Libertyville, Illinois. Web: http://www.variation.com/cpa

Taylor, A., J. Allen, and P. Clark. 2002. Extraction of a weak climatic signal by an ecosystem. *Nature* 416: 629–632.

Tomas, C.R., B. Bendis, and K. Johns. 1999. Role of nutrients in regulating plankton blooms in Florida Bay. In *The Gulf of Mexico large marine ecosystem: Assessment, sustainability, and management*, ed. H. Kumpf, K. Steidenger, and K. Sherman, 323–337. Malden: Blackwell Science.

Zieman, J.C., J.W. Fourqurean, and R.L. Iverson. 1989. Distribution, abundance and productivity of seagrasses and macroalgae in Florida Bay. *Bulletin of Marine Science* 44(1): 292–311.

Wang, J., J. Van De Kreeke, N. Krishnan, and D. Smith. 1994. Wind and tide response in Florida Bay. *Bulletin of Marine Science* 54: 579–601.

Williams, C., J.N. Boyer, and F. Jochem. 2008. Indirect hurricane effects on resource availability and microbial communities in a subtropical wetland-estuary transition zone. *Estuaries and Coasts* 31: 204–214.

Woodall, W.H. and B.M. Adams. 1993. The Statistical Design of CUSUM Charts. *Quality Engineering* 5: 559–570.

Further Reading

Boyer, J.N. 2004. The value of a regional water quality monitoring network in restoration planning in South Florida. EMAP Symposium, May 6, 2004—Newport, RI.

Briceño, H. and A. Callejon. 2000. Chemostratigraphic correlation of the Source Rock in the La Luna K-T(!) Petroleum System in Southwestern Venezuela. *In* Paleogeography and hydrocarbon potential of La Luna Formation and related Cretaceous anoxic systems, Proceedings SEPM Research Conference 2000, Venezuela

Rudnick, D., C. Madden, S. Kelly, J. Boyer, S. Blair, K. Cunniff, and C. Kelble. 2007. *Disturbance and ecosystem change in Florida Bay and Southern Biscayne Bay.* Providence: Estuarine Research Federation Conference.

Steidinger, K., W. Richardson, M.B. Neely, G. McRae, S. Richards, R. Bray, T.H. Perkins, and C.R. Tomas. 2001. Florida Bay microalgal blooms. 2001 Florida Bay Science Conference, Key Largo, Florida USA.(Abstract)