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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.

KEY WORDS: Florida Bay; chlorophyll a; time-series; climate signal; CUSUM; hurricane impact

INTRODUCTION

Two of the most important challenges of global change ecological research are to be able to detect ecosystem changes while they are happening and to directly tie these changes to the pertinent environmental drivers. This is especially true when dealing with phytoplankton, as individuals and populations vary over weeks while 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). That domination of an individual species or community type lasts only a few weeks and occurs at specific times of the year suggests that they are regulated by changing endogenous and exogenous factors (Belgrano et al. 2004).

Most data sets generated during surveys and monitoring programs to establish temporal and/or spatial variations and trends are usually interpreted by analyzing time-series, where one of the axes is either time or distance. Due to the intrinsic characteristics of natural phenomena, data are strongly affected by sturdy serial correlation and wide variations which may mask the underlying pattern components (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 between engineering and environmental sciences is that, in the latter, observations are rarely collected at regular spacing, 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 Thompson 2001). Another problem is that climate-related time series usually contain combinations of variables measured at different time scales and at disparate locations. That the effects variables may be measured far from the forcing variables is a problem to be resolved (Mann et al. 1999).

In the present study we attempt to establish links between biogeochemical descriptors of water quality to external drivers, natural and anthropogenic, by contrasting time-series of data. First, using Florida Bay as an example of a sub-tropical estuary, we perform statistical analysis to subdivide the bay into zones having similar biogeochemical characteristics and then compare them to highlight their defining and unique properties in space and time. Finally, we compare their evolution since 1989 with those of the potential global and regional climatic stressors such as North Atlantic Oscillation (NAO), Atlantic Multidecadal Oscillation (AMO), precipitation rate, storms, Accumulated Cyclone Energy (ACE), natural and managed freshwater supply from the Everglades, and responses from the system, especially chlorophyll *a* (CHLA) as an indicator of phytoplankton biomass.

METHODS

Site Description

Florida Bay is a large (2000 km^2) and shallow (average 1.5 m), estuarine lagoon located at the southern end of the Florida Peninsula (ca. 25º 05'N, 80º 45'W), between the Everglades swamps and marshes to the north and the Florida Keys to the south and east; westwards it is open to the Gulf of Mexico (Fig. 1). Florida Bay includes shallow basins separated by grassy mud banks and except along its western portion, tides have little effect on the water levels of the bay because these 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 y^{-1}); the remaining 10% is by runoff from the Everglades region and mostly from managed canal discharges (Nuttle et al. 2000). About 75% of the precipitation occurs in the wet season (Schomer and Drew 1982) from May to October. Mean annual water temperature is 24.5 °C; mean monthly low temperature is 20 °C in January and a mean monthly high temperature of 28 °C in August. Tropical storms and hurricanes regularly impact the bay by modifying its geomorphology, suddenly decreasing salinity, remobilizing and redistributing bottom sediments, destroying vegetation cover and changing the water nutrient concentrations.

Data Collection

A network of water quality monitoring stations was established by Florida International University (FIU) for Florida Bay beginning in 1989 (Fig. 1), where 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).

Briefly, monitoring included field measurements of surface and bottom salinity (practical salinity scale), temperature (°C), dissolved oxygen (DO, mg l^{-1}), and turbidity (NTU). 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 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), compared to a standard curve of pure CHLA (Sigma) and reported in µg l-1. Details of sampling methodology and laboratory analysis have been described elsewhere (Boyer and Fourqurean 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 and named such zones “zones of similar influence” (ZSI). We reassessed their subdivisions using the now longer water quality data set extending to 2007 by applying factor analysis and hierarchical clustering as statistical tools. From the total period of record (POR) extending from 1989 to 2007, we selected only data points for which all parameters had been reported from March 1991 to December 2007, and included 13 biogeochemical variables in the model: TOC, TN, TON, TP, CHLA, SRP, NO_2^-, NO_3^-, NH_4^+, salinity, turbidity, temperature, and DO.

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 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 5^{th} and 95^{th} percentiles. Non-parametric Mann-Whitney tests were used to compare biogeochemical variables among ZSI and also between wet and dry seasons.

<u>Normalized Cumulative Sum Charts</u>

After subdividing FB 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 first 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….n) from a target specification (T) against n, the sample number (Ewan, 1963; Woodall and Adams 1993). For our analysis we use 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 McKenzie 2000) which removes high frequency noise and smoothes the data. This direct and easy connection between CUSUM and process performance has recently driven 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 multiple of standard deviation, allowing an expedite 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 a secular 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 subperiods before and after a significant shift in the cumulative z-score plots were independently tested for significance using the nonparametric Mann–Whitney test.

RESULTS

Subdivision of FB by PC-Cluster analysis

Our factor analysis rendered 6 main factors (F1 to F6; $p<0.05$)) which explain 79.1% of the variance. Varimax rotation allowed direct link of these factors to specific water quality parameters controlling their structure as shown in Table 2. F1 is mostly a function of TN, TON and TOC; F2 is 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 is highly correlated with SRP; and F6 is 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 a highly robust and long-lasting relationship among variables.

We calculated the mean, standard deviation, median and median absolute deviation (MAD) for the factor scores for each one 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

<u>Northern Bays</u>

The NB includes the 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 tides or the influence of marine waters. Salinity and nutrient concentrations react quickly to rainfall and inflow from creeks draining Taylor Slough and C-111 canal overflow across the panhandle by experiencing sharp freshening during high flows and developing a steep salinity gradient with more saline waters to the south and southwest (Cosby et al. 2005). During drought periods hypersalinity up to 54 may develop.

NB has been a traditionally bloom-free zone, with the lowest median CHLA concentration in Florida Bay (median=0.64 μg l^{-1}; Table 3). Low incidence of blooms is the result of extreme P limitation caused by low P contribution from the Everglades combined with Ca-rich sediments that immobilize the already scant P supply (Boyer et al. 1997; Fourqurean and Robblee 1999). Calculated climatology for CHLA (Fig. 3) and Mann-Whitney test indicate that CHLA in NB is significantly lower in the wet season (May-Oct) 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. The lack of information on the species composition and dynamics of zooplankton communities in NB hinders further insight on its cause.

Eastern Florida Bay

FBE, located at the extreme northeast portion of FB (Fig. 1), is mostly unaffected by tides or influenced by 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 is very low (median=0.49 μg l^{-1}) in FBE and concentrations are 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 is greater during the latter (Fig. 2).

Phytoplankton blooms were practically absent in FBE until the anomalous hurricane season of 2005, when an extensive cyanobacterial bloom developed (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., *Prorocentrum micans*), and small cyanobacteria making the major fraction of cellular biovolume (Phlips and Badylak, 1996; Hunt and Nuttle 2007). An interesting observation is that of Steidinger et al. (2001), who reported a change in predominant phytoplankton taxa in eastern FB from dinoflagellates during fall 1994 to early summer 1995 to cyanobacteria prevailing from late 1996 to spring 1997.

<u>East Central Florida Bay</u>

FBEC is located north of Key Largo (Fig. 1) between 80º 30' and 80º 40' west. Freshwater from the Everglades is supplied by Taylor River, Mud Creek, East Creek and mostly by Trout Creek (up to 32 $m^3 s^{-1}$) along its northern boundary. CHLA (median=0.33 $\mu g\ l^{-1}$) is the lowest for FB especially during the wet season (Table 3; Fig. 3). Its median TN:TP ratio of 99.7 is 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 X $10^5\ \mu m^3\ ml^{-1}$ 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 but with cyanobacteria as the minor component. According to Hunt and Nuttle (2007) and Hitchcok 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 covers the north central portion of FB (Fig. 1), as a rather isolated basin where scarce freshwater run-off from the Everglades is supplied mostly by McCormick Creek towards its NE end and Alligator Creek to the NW, developing an internal north-south salinity gradient within FBC. Timing and volumes of precipitation and run-off play a significant role on FBC conditions, where hypersalinity occurs periodically reaching up to 70 during periods of low rainfall and high evaporation (Boyer 2004; Robblee et al. 2001). Besides having the highest nutrient concentrations FBC also displays the widest nutrient concentration range and a median TN:TP ratio of 53 which is intermediate between the highest value in FBEC (99) and the minimum of FBW (24). As a probable consequence of nutrient enrichment, median CHLA (1.53 µg l^{-1}) is the highest and also affected by a wide range of concentrations (35.5 µg l^{-1}). This character is evident in its well developed seasonality for CHLA with maximum bloom activity 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 where Redfield ratios will be reached, contributing to enhanced productivity (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 exceeding 1.0 x 10^7 μm^3 ml^{-1}, with other cyanobacteria, diatoms and dinoflagellates in a secondary role. Nevertheless, Tomas et al. (1999) indicated that diatoms are the major component, especially at Rankin Lake, where addition of silica readily 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; Richardson, 2001)., improved efficiency to compete for P at low concentrations, here underscored by the largest alkaline phosphatase activity level (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)

<u>Southern Florida Bay</u>

FBS occupies the south central portion of FB, coinciding with Phlips et al (1999) "South Central" zone of phytoplankton communities. Besides rainfall contributions, FBS waters are affected by currents moving from FBC and the exchange along the passes in the Florida Keys to the south. TN:TP median ratio is 77 indicating P limitation for seston and CHLA is moderate (0.54 μg l^{-1}) with maximum values in the dry season (Fig. 3). Biovolume studies (Phlips et al. 1999) indicate that phytoplankton assemblages are dominated almost exclusively by *Synechococcus* cf. *elongatus* with blooms occurring from October to January as a consequence of wind-driven circulation moving phytoplankton-rich waters south from FBC (Hitchcock et al 2007).

Western Florida Bay

FBW covers the highly dynamic western extreme of FB with an open boundary with the Gulf of Mexico but isolated from direct overland freshwater sources. Tidal regime affects FBW significantly (Wang et al. 1994) and causes short residence time and salinities close to marine levels in its waters. FBW median TN:TP ratio of 25 is slightly above Redfield ratio, but not reflecting a major N limitation, and median CHLA (1.30 μg l^{-1}) is relatively high. Contrasting with the rest of FB, 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 last 40 years to isolate specific shifts or trends, which could have a forcing role on water quality and phytoplankton biomass. The focus was on the North Atlantic Oscillation (NAO), the Atlantic Multidecadal Oscillation (AMO) index and tropical cyclone activity as they relate to regional and local phenomena such as precipitation over the bay, managed flows 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 trend exhibits substantial interseasonal and interannual variability with the negative phase of the NAO, which prevailed from the mid-1950's to early 1979 (Hurrell 1995), with a below average rainfall period extending in the Z-CUSUM chart from 1970 to mid-1982 (Fig. 4). In mid 1982 NAO values shifted towards above average levels displaying two cycles of about 3.5 years each. Then, in 1989 a highly positive NAO phase began (steep positive slope) which persisted until mid 1995. Finally, a return to strong negative phases began in late 1995 which with some abrupt oscillations in 1998-2000 persisted until August 2008. Strong positive NAO phases (positive slopes) result in warmer temperatures and higher precipitation in eastern United States with negative phases producing opposite results (Hurrell 1995). Statistically significant change-points were detected in December 1988, April 1995 and April 2008 with 93%, 100% and 91% confidence level (CL) respectively. The sharp break in 1995 would be associated to a multidecadal change from cool-dry to warm-wet climate.

The Atlantic multidecadal oscillation (AMO) which expresses the variability of the North Atlantic sea surface temperature (SST) field (Kerr 2000), has been considered a major climate driver over the Atlantic tropical region (Delworth and Mann 2000), with cool-dry and warm-wet climate linked to AMO negative and positive 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 phase for the North Atlantic basin was in effect during 1970-1990 (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 (CL)=96%), suggesting a shift to higher SST and higher precipitation rates.

In keeping with the aforementioned trends, the period from 1970 to 1994 experienced low tropical cyclone activity, in terms of number, frequency, and strength of hurricanes (Category ≥ 3 in the Saffir-Sympson scale) (Landsea et al. 1999; Goldenberg et al. 2001). This interlude was immediately followed by the record breaking period of high cyclone activity and precipitation rate from1995 to 2005. Figure 4 also shows the Z-CUSUM charts for number of hurricanes and the Accumulated Cyclone Energy (ACE) for the period 1970-2006. The ACE is an index that combines the numbers of storm systems, how long they exist, and how intense they became. 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 our analysis in the FB region come from 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 to construct cumulative curves. These data sets have similar Z-CUSUM patterns and display high frequency seasonality, partial tendencies and cycles of diverse span and amplitude. We explored the consistency of these patterns in the region and there is a clear coincidence in rainfall tendency that extends further north to other stations at Tamiami, Miami Airport, and West Palm Beach stations. Hence, we used the Everglades LTER station as representative of rainfall in the study area. From 1970 to May 1990, precipitation was generally below average except for a short increase in 1982-1984 (Fig. 5). Besides seasonality, shown as a high frequency signal, 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% 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 to finally convey into FB are closely tied to precipitation rate (Fig. 5). The flow volume signal mimics that of precipitation, except for events of extremely high flows delivered before major storms which would cause sudden drops in salinity and nutrient load unbalance causing major disturbances in the bay. Additional information to substantiate further the shift 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 FB, hence, in final water availability in the bay (rain plus canal flows). 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 Phytoblankton Biomass

Besides affecting salinity dynamics, the amount, intensity, and distribution of precipitation should have additional impacts on FB. Tropical storms and hurricanes regularly impact the bay and modify its geomorphology, and hence, its circulation and salinity patterns. Nutrient concentration changes are imposed suddenly as sediments are resuspended and redistributed, not to mention destruction of sub-aquatic vegetation and making bottom sediments more prone to erosion. This new set of conditions imposed by hurricanes on the ecosystem drive significant responses from planktonic organisms, especially as changes in CHLA in the water column.

A common feature of all zones of the bay is 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 Figure 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 is centered around 1994-1995. As observed, hurricane impacts reveal themselves as sudden increases in CHLA. The regime system shift (SS) is best displayed in FBE and FBEC by drastic decreases in CHLA concentration of 57% and 70% respectively, while in FBC we observe a milder decline (26%) in 1994 and a stronger one in 1995 (46%). In FBS the shift occurs in March-April 1995 representing a 60% decline in CHLA. In NB it is more difficult to define a break directly connected to the SS, but it seems to occur in late 1993, preceding the changes in other ZSI and coupling more closely with the shift in SST towards a positive phase on the summer of 1994 (Enfield et al. 2001). Finally, in FBW the shift to lower CHLA in 1994 is not present.

Hurricanes Mitch (M) and Georges (G) impacted Florida Bay in 1998 and their effects were mostly felt in FBC, FBW and FBS causing their CHLA level to increase, especially in FBC (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 impact to the central and western portions of FB. Harvey and Irene initiated the largest and most sustained bloom in the record for the central and western portions of FB (Boyer and Briceño 2007). In NB and FBEC the impact on CHLA was relatively smaller while in FBE it was relatively minor. The disturbance caused by hurricanes Katrina, Rita and Wilma (KRW) the summer/fall of 2005 was the largest recorded for NB and FBE, areas traditionally known by their very low CHLA levels (Figs. 2 and 6). In FBEC and FBC the impact of KRW was relatively minor and in FBS and FBW was even milder.

DISCUSSION

Deterioration of water quality in FB in the late 1980s leading to increasing frequency and magnitude of phytoplankton blooms and the onset of massive seagrass die-offs in 1988 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). Apparently opposed to that generalized perspective is the blame put on anomalous pulses of freshwater from the Everglades imposed by water management 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 monitored period 1989-2007 we attempted to establish a link between potential drivers and ecosystem response to explain those changes occurring in water quality and the disparity of those responses in a geographical context.

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

Strong positive NAO phases engender warmer temperatures and higher precipitation rate in eastern United States, while negative phases produce dryer conditions and drought (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 may have resulted in lower precipitation during 1988-1995 and increasing rain for 1995-2008. On the other hand, the Atlantic Multidecadal Oscillation (AMO) which fundamentally expresses the variability of the North Atlantic sea surface temperature field (Kerr 2000) has been considered a major climate driver over the tropical Atlantic region (Delworth and Mann 2000). The effects of AMO have been specifically demonstrated in central and south Florida (Enfield et al. 2001), where rainfall has significant positive correlations for both AMO phases. Hence, drought periods correspond to the cool phase (negative), and rainfall is more copious when the Atlantic is in its warm phase (positive). AMO and NAO time-series experienced drastic shifts in June 1994 and April 1995 respectively, reinforcing their individual driving mechanisms and enhancing the system shift. In summary, these globally linked indexes, NAO, AMO, ACE, and hurricane development have a common and significant pattern regime shift in 1994-1995. Additionally, the well developed shift from prevailing negative to positive phases of NAO in the late 1980s (91% CL) was also observed (Fig 4).

A causal chain of meteorological, hydrological and ecological processes linked to NAO, AMO and ACE and storm and hurricane frequency was attempted with CHLA as a proxy for phytoplankton biomass. Similar proxies using CUSUM methodologies have been proposed for phenological changes in copepod communities in the Ligurean Sea (Molinero et al 2005) 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.

The differential magnitude of disturbance (amplitude of deviation in Z-CUSUM charts, Fig. 6) caused by the combined impact of tropical storm Harvey and Hurricane Irene (higher on FBC, FBS and FBW) as compared to the one produced by Katrina, Rita and Wilma (higher on NB and FBE) may be explained by their spatial occurrence and precipitation totals. Terrestrial runoff from tropical storm Harvey and Hurricane Irene conveyed 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 two-fold increase in their NH_4^+ and SRP levels. Shark River estuary waters developed a plume into the Gulf of Mexico which circulated around Cape Sable to finally mix with FBW and FBS waters (Hitchcock et al. 2007) fueling a major phytoplankton bloom. The effect of these runoff events in 1999 was also felt in eastern FB but the magnitude was smaller.

The impact of Hurricanes Katrina, Rita, and Wilma in 2005 was concentrated in eastern FB. Rudnick et al. (2007) support the hypothesis that this bloom was the system response to both natural and anthropogenic drivers which unfortunately coincided in space and time. Previous to Katrina, construction work associated to the widening of US Highway 1 included mangrove forest clearing, in situ mulching, and mixing with soil, all of which increased TP leached into the adjacent waters. Additionally, canal discharges were increased considerably as a prior flood control measure to mitigate Katrina impact. Combined water input from discharge and Katrina increased to over 30 million m^3 in August. The sudden freshening caused massive SAV die-off whose detritus, combined with benthic flux from sediment resuspension produced by hurricane winds, increased TP and TOC concentrations and after Rita (September) initiated a cyanobacterial bloom which reached regional extension in November 2005 (Rudnick et al. 2007). Since then, the bloom has been sustained by the long water residence time of the basins and further SAV mortality due to increased turbidity. As of April 2008, CHLA in FBE had not yet returned to levels prevailing before the 2005 hurricane season.

The disparity of ecosystem response (i.e. CHLA) to hurricane stress is apparently due to proximity of track, magnitude of the event (i.e. precipitation, wind strength) and environmental conditions pre-event and post event (Williams et al. 2008). Hurricane Irene made landfall on western FB and discharged record precipitation (over 60 mm) on FB. 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.

The conflicting hypothesis as to the cause of ecological degradation of FB since the late 1980s (i.e. seagrass die-off and bloom persistence), with some authors blaming high salinity due to lower water supply from the Everglades (Robblee et al. 1991;

Fourqurean et al. 2003; Hunt and Nuttle 2007) and others holding responsible lower salinity and increased nutrient supply from the Everglades (Brand 2001), may in fact both be correct. We could conceive FB as a system that is steadily responding to decadal or multidecadal forcing that dictate the baseline of response. On that baseline phenological dynamics outlines the seasonal variability, and short-lived events (hurricanes and/or canal discharges), departing from "normality" are imposed on the system to later (a few months) return to pre-event conditions The behavior of CHLA and total nutrients (TN, TP and TOC) in each and all compartments of FB seem to adapt to that model along the monitoring period, displaying a long-term declining trend across the bay on which seasonal oscillations are superimposed, and only interrupted by events of sudden increase followed by a relatively rapid return to pre-event conditions trailing the long-term trend. This apparently robust behavior, suggesting some degree of resilience, needs to be considered with caution, mostly when substantial efforts and resources are being devoted to restoration of the Everglades and Florida Bay, where ecosystems are extremely fragile and thresholds may be breached leading to a cascade of undesired deterioration.

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