

Evaluating Linkages of Weather Patterns and Water Quality Responses in South Florida Using a Synoptic Climatological Approach

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ABSTRACT

Coastal ocean ecosystems are impacted by atmospheric conditions and events, including episodic severe systems such as hurricanes as well as more regular seasonal events. The complexity of the atmosphere–ocean relationship makes establishing concrete connections difficult. In this paper, this relationship is assessed through synoptic climatological methods, a technique well established in applied climatological research but heretofore rarely used in assessing coastal ocean water quality and ecological status. Historical sea level pressure data are used to define 10 circulation patterns across the southeastern United States and adjacent Gulf of Mexico, based on the spatial pattern of sea level pressure, which can then be associated with the presence of cyclones, precipitation, and wind stress. The frequency of these patterns, and their deviation from climatological means, is then compared with Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) chlorophyll observations over the Florida Bay and south Florida shelf for the period 1997–2010. Several circulation patterns indicative of cyclonic activity over the broader region are associated with increased chlorophyll levels in the study area, while several other patterns, indicative of anticyclonic conditions, are associated with decreased chlorophyll levels. These relationships are spatially and temporally variable, generally with stronger correlations observed in winter and spring, and farther north in the study region when compared with more southern locations near the Florida Keys. The results here demonstrate the potential of using synoptic analysis and derived statistics for tracking and modeling changes in chlorophyll and other indicators related to water quality and biological health.

1. Introduction

South Florida coastal ecosystems are particularly sensitive and inherently linked to short-term perturbations in weather and climate. Episodic hurricanes and regular-interval winter storms alter winds, temperatures, and precipitation patterns, and modify circulation and transport of materials in and out of Florida Bay, the

west Florida shelf, and the Florida Reef tract (He and Weisberg 2003; Ault 2006). Ault (2006) conducted an extensive review of biological oceanography for the region and attributed synoptic-scale processes and event-based meteorological forcing as likely controls on temporal and spatial distributions of chlorophyll and phytoplankton (algal) abundance. Del Castillo et al. (2000), Gilbes et al. (2002), and Morey et al. (2009) detailed the importance of riverine discharge in the context of offshore phytoplankton plumes, and increases in productivity along the west Florida shelf. Also well documented are the strong upwelling (winter) and downwelling (summer) seasonal

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flow structures and associations with weather forcing in the region (Liu and Weisberg 2007). He and Weisberg (2003) and Liu and Weisberg (2007) attributed wind forcing as a dominant mechanism for shelf transport and summarized the corresponding nature of severe synoptic weather events with upwelling–downwelling current patterns. Yang and Weisberg (1999) identified an upwelling maximum seaward of Tampa Bay, Florida, and suggested this maximum could further enhance phytoplankton biomass by adding nutrients from the shelf with those of estuarine origin from Tampa Bay.

Synoptic-scale weather events, coupled with dynamical ocean processes and cycles and compounded by human activities, are further linked to known problems in coastal water quality and biological health in the region. The early 2002 “black water” event and harmful red tide (*Karenia brevis*) blooms along the Florida Bight were believed to result from a combination of factors stemming from excessive rainfall–discharge and increased hurricane activity, among others (SWFDOG 2002; Hu et al. 2003a, 2006; Neely et al. 2004; Vargo 2009). The excessive and widespread algal blooms along the southwest Florida shelf in autumn–winter 2001/02 and the dark water plume in 2003 corresponded with midlatitude cyclone activity that produced locally intense rainfall, and subsequent wastewater overspill and/or release (Hu and Müller-Karger 2003; Hu et al. 2004). In related work, Briceño and Boyer (2010) summarized the importance of tropical and extratropical cyclones to phytoplankton and water quality response, suggesting a further link of climatic events to historical episodes of sea grass die-offs and excessive algal blooms in the region.

Although evidence strongly supports a causal relationship between proximate, seasonal weather variations and ecosystem response, multidisciplinary research efforts aimed at linking weather to ecosystem-level indicator response and change have not been fully explored or resolved. Instead, the majority of research focus has been on rendering global-scale climate models, and relating broad-scale patterns or atmospheric teleconnection indices to local-scale processes and change, with only moderate success (Stenseth et al. 2003; Kimmel et al. 2009). Problems with these studies often result because ecosystem conditions and processes are most often reflected on shorter temporal intervals and smaller spatial scales than those utilized to derive teleconnection patterns and indices. Thus, singular important events such as heavy rainfall–discharge episodes, strong frontal passages, or tropical cyclone activities are difficult to assess using such broad indices. To address this issue, an approach that characterizes these higher-frequency modes of variability in weather and ocean behavior could provide a more conceptually detailed and resolved understanding

of critical climate–ecosystem processes and mechanisms at work in the region.

One such approach to better understand these complex time–space mechanisms associated with weather variation and local ecosystem response is through synoptic climatology. Synoptic climatology represents a holistic approach in categorizing atmospheric conditions and then assessing the relationship between the atmosphere and an environmental outcome (Yarnal 1993). Synoptic methods aim to integrate weather conditions by synthesizing information from multiple variables and/or locations, and using this information to effectively partition local or regional weather variability across several distinct recurring patterns or types that can be thought of as complete “weather situations” (Sheridan 2002). Synoptic methods have been incorporated in environmental research in a number of fields, from heat-health warning systems (e.g., Sheridan and Kalkstein 2004) to extreme snow ablation episodes (e.g., Bednorz 2009) and insect transport (e.g., Frank et al. 2008a,b). These methods have proven particularly applicable for coastal–estuarine ecosystems that cannot be clearly linked to global-scale climate forcing (Stenseth et al. 2003), though it has only been fully utilized in one recent study, which addressed the variability of biotic components and ecosystem structure in Chesapeake Bay (Kimmel et al. 2009).

Thus, while there have been ample case studies that have connected atmospheric conditions and ocean ecosystem response during specific extreme events such as hurricanes, far less is understood about the long-term relationship between the variability in the frequency of seasonal weather features and ocean physical and biogeochemical properties on local ecosystem scales. Here, we address this need by examining whether changes in the frequency of atmospheric circulation patterns can be associated with an ocean response. Specifically, we examine the association between the frequency of sea level pressure patterns across the Gulf of Mexico and changes in ocean chlorophyll values across the southern part of the west Florida shelf and the Florida Keys for the period 1997–2010. We use historical climate–modeled atmospheric sea level pressure data to define daily synoptic atmospheric circulation patterns, and satellite data from the near-daily Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) ocean color time series [National Aeronautics and Space Administration (NASA) SeaWiFS Project] to assess oceanic chlorophyll. Here chlorophyll is used as an indicator for water quality, phytoplankton abundance, and ecological state. Systematic connections between the two datasets are then identified that connect anomalous frequencies of synoptic circulation patterns to a chlorophyll response, which can then be used to assess potential

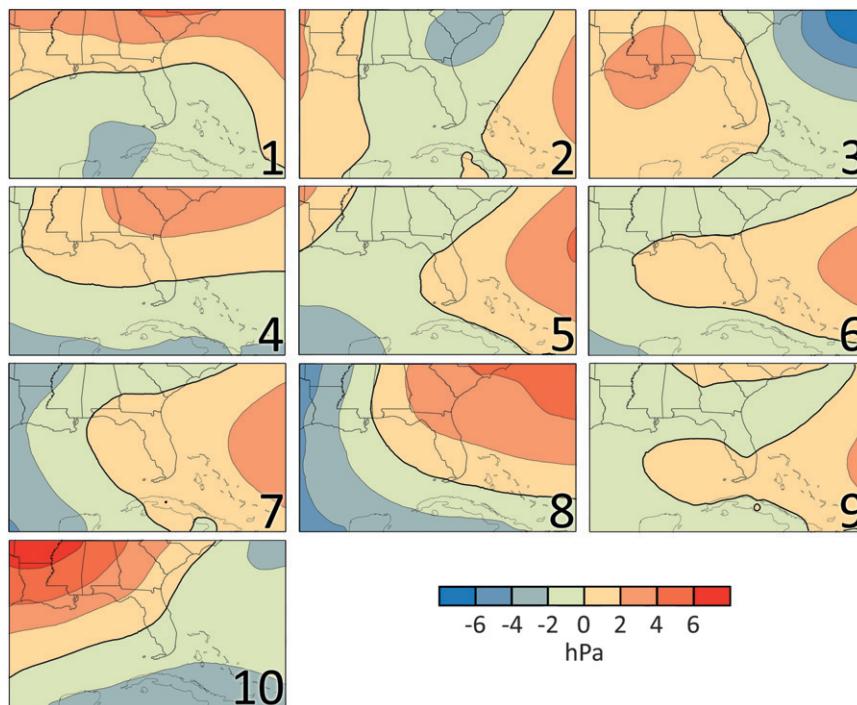


FIG. 1. Mean sea level pressure anomalies associated with each of the 10 CPs.

mechanisms that link ambient weather conditions to physical and biogeochemical seasonality and surface property response for the region.

2. Data and methods

For this study, methods were divided into three primary phases: 1) synoptic climatology development and classifications of 10 discrete circulation patterns (CP) from the North American Regional Reanalysis (NARR), 2) time series and climatology development of full- (1 km) resolution SeaWiFS chlorophyll, and 3) composite mapping and analysis of spatiotemporal patterns of water variable responses to CP occurrence and relative frequency.

a. Atmospheric data and SLP pattern classification

All atmospheric data used in this research were obtained from the NARR dataset. NARR contains significant improvements in hydrological modeling over previous reanalysis products (Mesinger et al. 2006), though there are still inaccuracies that have been observed in other regions (Bukovsky and Karoly 2007). To derive CPs, we first obtained 1200 UTC sea level pressure (SLP) data for the domain 20°–35°N, 95°–70°W, representing the spatial extent shown in Fig. 1. Of the 4503 data points acquired over this domain, only every tenth data point was utilized in the clustering procedure, resulting in 450 data points being incorporated. The selection of every tenth point

was based on research that has shown that too fine of a spatial scale is not optimal for defining broader atmospheric patterns, as too much weight is given to small-scale features (Demuzere et al. 2009). Similarly, Demuzere et al. also show that the resolution of cyclonicity is dependent upon grid scale, and hence a rather large overall domain was chosen to more adequately resolve the relevant synoptic-scale systems that affect the region of interest.

We defined synoptic weather types using standard principal component analysis (PCA) and cluster analysis (Yarnal 1993) to bin days into one of 10 CPs according to similarity of SLP fields. SLP data were subjected to a two-step classification procedure, incorporating a PCA followed by a cluster analysis. The goal of the PCA is to determine the primary modes of variability in the dataset, thereby reducing the size of the dataset, but also eliminating the inherent spatial autocorrelation of nearby SLP values and creating the completely uncorrelated variables necessary for use in a cluster analysis. The 12 principal component scores (PCs) with eigenvalues greater than one were retained for further analysis. In the second step, the retained PCs are then subjected to the two-step clustering component in the Statistical Product and Service Solutions (SPSS), Inc., proprietary software package, with 10 clusters retained. Once completed, this procedure classifies each day in the time series into one of 10 clusters representing the typical SLP patterns across the region.

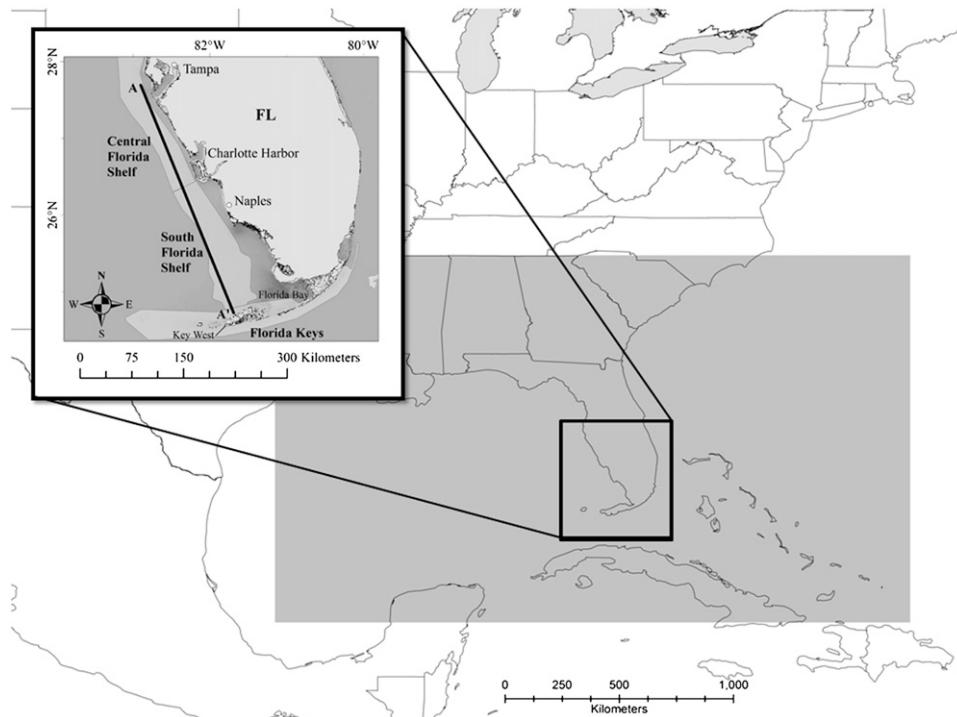


FIG. 2. Study area showing chlorophyll regions and transects used for SeaWiFS satellite data extractions. Gray-shaded region corresponds to the domain used in CP determination.

Several different modifications to the raw SLP data were assessed to determine the most optimal basis for classification. The permutation that best discriminated variability in chlorophyll is based on *daily spatial anomaly*. The daily spatial anomaly is derived by first calculating the daily mean SLP value across all 450 data points, and subtracting this mean from each gridpoint value. The daily spatial anomaly was chosen to delineate the overall pressure gradient field, which can then be related directly to wind stress and larger-scale atmospheric features; these anomalies were not standardized, as it was desired to maintain an absolute measure of the pressure gradient.

b. Satellite data processing

Satellite data include the NASA SeaWiFS data products of near-daily chlorophyll at 1-km spatial resolution. SeaWiFS Ocean Color level-2 archive products produced and distributed by the NASA Goddard Space Flight Center's Ocean Biology Processing Group include the geophysical values for chlorophyll *a*. The processing used the calibration and algorithm updates in 2011, defined in the software package SeaWiFS Data Analysis System (SeaDAS), version 6.2. Chlorophyll *a* was derived using the ocean chlorophyll 4-band algorithm, version 4 (OC4v4; O'Reilly et al. 1998). Chlorophyll *a* is the photosynthetic pigment in marine phytoplankton and a reliable indicator

of water quality and pollution impacts because of its sensitivity to ecosystem stressors, especially nutrient loading in the region (Boyer et al. 2009). Chlorophyll concentration ($\mu\text{g L}^{-1}$) is referred to simply as chlorophyll in this paper. Chlorophyll was estimated as the 5-day filtered mean value of observations, applied to each pixel in the time series. Filtering was applied on chlorophyll images for each Julian day in the time series and referred to here as the 5-day chlorophyll. A chlorophyll climatology was constructed using all individual satellite measurements, similar to methods applied in Hu et al. (2009) and Pirhalla et al. (2009). The development of consistent near-daily time series of SeaWiFS allowed for visual interpretation of chlorophyll and for the evaluation of spatiotemporal patterns of variability and linkages to CPs. Overall chlorophyll mean and variability estimates were computed by month using all available daily values. Image pixels were extracted and analyzed for three regions (central Florida shelf, south Florida shelf, and Florida Keys) and over a transect line for time series analysis (Fig. 2). Pixel artifacts and null values were removed prior to analysis using the NASA SeaDAS default settings. Chlorophyll values were log transformed to make their distributions normal, a requirement for first order statistics (mean and standard deviation) computations (Campbell 1995), as $C_J = \log(\text{chlorophyll}_J)$ and climatological mean as

$$\bar{C}_J = \frac{\sum_y C_{J,y}}{n},$$

where $C_{J,y}$ is the log-transformed chlorophyll on yearday J and year y and n is the number of days in the time series. A climatological chlorophyll anomaly was also calculated as

$$C'_{J,y} = C_{J,y} - \bar{C}_J,$$

where \bar{C}_J is the grand (long term) mean for yearday J of all years, and $C'_{J,y}$ is the climatological anomaly for yearday J of year y . Ocean color chlorophyll signals may be biased over nearshore waters because of the presence of a significant amount of colored dissolved organic materials, suspended sediments, and/or the shallow bottom (Hu et al. 2003b, 2005; Cannizzaro et al. 2013). For this study where focus is on climatological mean and variability patterns, algorithm errors are dampened because of the vast numbers of pixel observations (>1500 clear images) used in analysis. To account for potential algorithm biases, scalar quantities were extracted in shelf areas where chlorophyll estimates are considered more reliable (Cannizzaro et al. 2013).

c. Examining chlorophyll response and circulation pattern frequency

Five-day filtered chlorophyll imagery was matched with dates in the time series where each CP occurred, binned by month, then composited to determine surface property deviations from climatological normal conditions. Composited chlorophyll deviation maps were computed for each CP in each calendar month as the ratio of 5-day chlorophyll mean for dates when the CP occurred over the 5-day climatological mean as

$$\text{Deviation}_{J,CP} = \frac{\overline{C_{J,CP}}}{\bar{C}_J} - 1.$$

Deviations that were statistically significant from zero ($p < 0.1$, using Student's test with two tails) were also recorded in the resultant maps.

To assess the lag-response relationship between weather and chlorophyll beyond the seasonal cycles, anomalous conditions were also assessed. Anomalous frequencies of CPs for a given day were calculated by first calculating the number of occurrences of each CP for the centered 29-day period around the day, and from this subtracting the mean frequency of each CP for the same 29-day centered period across all calendar years in the dataset. The relationship between anomalous CP frequency and chlorophyll was assessed via correlation analysis, with

TABLE 1. Mean frequency of each of the CPs by month in percentage of all days.

	CP									
	1	2	3	4	5	6	7	8	9	10
January	2	10	20	2	11	4	4	22	3	22
February	3	8	15	5	12	5	9	17	5	22
March	2	12	13	9	11	6	13	15	6	13
April	1	9	11	12	12	8	22	10	7	8
May	2	4	4	20	7	15	29	3	13	3
June	2	3	1	14	3	24	30	2	21	<1
July	2	2	<1	4	2	52	14	2	23	<1
August	4	6	1	10	2	36	9	4	27	<1
September	12	10	3	25	6	12	10	6	11	6
October	7	8	6	33	7	6	7	8	7	12
November	4	12	11	14	8	6	4	20	3	18
December	2	9	16	6	9	5	4	24	2	22
Annual	4	8	9	13	7	15	13	11	11	10

an effective sample size adjustment to account for the high temporal autocorrelation in the datasets (Von Storch and Zwiers 2004):

$$N' = (N) \frac{1-r}{1+r},$$

where N' is the effective sample size, N is the original sample size, and r is the Pearson correlation coefficient at lag 1.

Following correlation analysis, selected CPs were grouped as aggregates that exhibited the most significant correlation with chlorophyll over seasonal to annual cycles. Two circulation pattern aggregates (CPA)—combining CPs 1, 2, and 3, representing more cyclonic patterns (hereinafter, cyclonic CPA), and CPs 4, 5, 6, and 9, representing anticyclonic patterns (anticyclonic CPA)—were calculated as the sum of anomalous frequencies for the respective CPs over the time series, and binned by month. After binning, dates that matched above and below the 75th and the 25th percentiles, respectively, over the anomalous frequency distribution were used to define a new set of chlorophyll ratio maps representing climatological chlorophyll response scenarios. Composited chlorophyll deviation maps were calculated using the same procedures as with the individual CPs and chlorophyll ratio maps.

3. Results

a. Pattern descriptions

The 10 CPs identified are discussed below and shown in Fig. 1; monthly mean frequencies are shown in Table 1. As with all synoptic climatological patterns, it should be noted that the descriptions and maps are for mean

conditions, and that conditions on any one given day that is clustered into one of these patterns may be somewhat different. Mean temperature anomalies, wind fields, and precipitation patterns were calculated for each CP; these are discussed qualitatively below but not shown because of space considerations.

- 1) The *eastern gulf flow* pattern features a low pressure center between the Florida Keys and Cuba, with a relatively strong pressure gradient across the Florida Peninsula. This pattern has a strong seasonality, peaking in September at 12%; other than between August and November, it does not occur on more than 3% of days in any month. In its peak season, it is associated with substantial rainfall across south Florida and significant wind, and usually represents a tropical cyclone or remnant low pressure area.
- 2) The *Carolina low* pattern features a well-defined trough of low pressure extending south from South Carolina across the Florida Peninsula. This pattern occurs relatively infrequently year-round, with average frequency between 8% and 12% between September and April, falling to less than 5% during the summer. This pattern is generally associated with a frontal system across the eastern United States, extending down into Florida. Cloud cover and precipitation are common across south Florida with this pattern, with above-normal temperatures in the winter and near-normal temperatures in summer.
- 3) The *Atlantic low* pattern features the largest pressure gradient across the broader region of study. This pattern has a strong seasonality, peaking during winter (January; 19%) and disappearing almost entirely in summer. This pattern features a very strong low pressure center well to the east of the North Carolina coast, and would likely represent a rapidly deepening extratropical cyclone in the western Atlantic Ocean. Conditions across south Florida are dry but windy, with well-below-normal temperatures during peak seasonality.
- 4) The *East Coast high* pattern features a broad area of high pressure, extending over the entire eastern coast of the United States down to Florida. A bimodal distribution occurs, with CP 4 most common in September (25%) and October (32%); followed by a secondary maximum in spring, peaking in May (20%). Weather conditions with this pattern are generally fair and seasonable.
- 5) The *approaching front* pattern features a trough of low pressure extending in a northeast-to-southwest axis across the southeast, to the west of Florida. This pattern occurs on 8%–12% of days between November and April, and largely disappears in summer. It usually occurs with a frontal system approaching Florida from the west, with the front extending northward toward a low pressure center near the eastern Great Lakes. CP 5 is generally seasonally warm and cloudy, but with little precipitation in south Florida, as it remains farther to the west.
- 6) The *mean summer flow* pattern is representative of long-term climatology in the summer with a Bermuda high off the Atlantic Coast and a slight pressure gradient extending westward. It is the predominant summer pattern, comprising 52% of all July days; decreasing to around 5% of days from October to March. It is associated with fair weather, weak winds, and near-normal temperatures in summer, but above normal in other seasons.
- 7) The *southern plains front* pattern is representative of another transitional situation with the typical scenario of a front extending southward across the southern U.S. plains from a low pressure center to the north. Sandwiched between an advancing front and high pressure to the east, south Florida has southerly flow, with warm temperatures, and generally fair conditions. This pattern increases in frequency in spring, peaking in May and June (around 30% of days) before falling off rapidly in frequency in July and remaining uncommon for the remainder of the season cycle.
- 8) The *western gulf low* is similar to CP 7 except that there is a stronger pressure gradient, and as a result it tends to occur more in the cold season: it peaks in occurrence at around 20% of days from December through February and largely disappears in summer. With a return flow from the southeast, south Florida experiences normal to above-normal temperatures, with fair skies and little precipitation.
- 9) The *weak trough* is an ambiguous pattern featuring a generally weak pressure gradient with a weak trough of low pressure over the northern Florida Peninsula. This pattern is summer dominant, occurring on 25% of all August days, while occurring less than 5% of the time in the winter. During late summer this may be a weak tropical disturbance, while in other seasons it is likely a remnant frontal boundary from a mid-latitude cyclone. It is associated with warmer-than-average weather in the winter and near seasonal thermal conditions in other seasons, but convective precipitation and cloudier than normal conditions, concentrated in the northern Florida Peninsula.
- 10) The *cold-core high* also features a large pressure gradient, except with a large area of high pressure over the eastern United States. Sea level pressure is above normal across the entire region, and with strong northerly advection, much of the region is

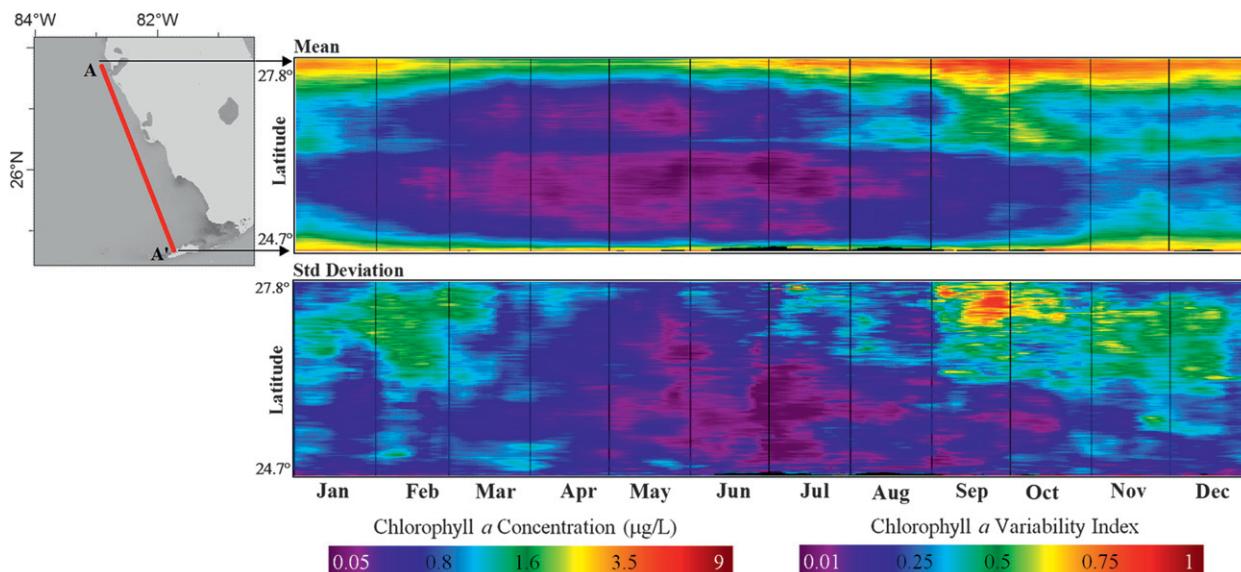


FIG. 3. Climatological summary of 5-day (top) running mean (expected) conditions of chlorophyll and (bottom) chlorophyll variability during a typical annual cycle along a north–south latitudinal transect line from approximately Tampa Bay to Key West. Note increases in variability along the upper transect during autumn (September–December) and late winter (February).

much colder than normal, although south Florida is only slightly cooler than normal, with dry, sunny, and windy conditions. This pattern peaks in winter, occurring on around 20% of days, and disappears in summer.

b. Seasonal patterns of ocean color

Hovmöller plots display the seasonal timing of chlorophyll mean and variability peaks along a north–south transect off the west coast of Florida (Fig. 3). As expected, the spatial pattern of chlorophyll includes higher mean concentrations near the coast than in open waters, with a broader area of higher chlorophyll found in the waters adjacent to Tampa Bay and just north of Key West, Florida. Temporally, higher mean values can be found from the hurricane season in late summer and the winter.

Greater variability is observed slightly offshore than in the nearshore waters, with higher values again during hurricane season and late winter. Along the transect in Fig. 3, annual patterns depict a peak in chlorophyll variability in September at the height of the hurricane season. In October and November, variability increases from the north, mainly distributed off the coast from Tampa to just north of Naples, Florida. Winter patterns exhibit heightened variability along coastal sections of the Florida shelf, when periods of enhanced upwelling occur (Liu and Weisberg 2007). March represents a transitional month with more southward distribution of heightened variability north of Key West. Variability then decreases

significantly in spring and summer at the peak of the wet season, when downwelling-favorable patterns arise.

c. Ocean color–circulation pattern associations

Composite imagery of chlorophyll ratios for each CP reveals the synoptic patterns associated with positive and negative chlorophyll response during the year (Fig. 4). Seasonally, a greater differentiation of chlorophyll levels among the CPs is seen during a broad transition between February and May, and during hurricane season from August to November. During winter and summer, as is typical with year-round synoptic classifications, fewer CPs occur (most notably in July, when only two CPs (6 and 9) together comprise 75% of days in the historical record). Thus, during these months there is a tendency for fewer chlorophyll anomalies to occur.

Several patterns show clear associations with anomalous chlorophyll levels. Three CPs (1, 2, and 3) are all associated with active cyclones in the region, and hence are connected to increased pressure gradients, wind stress, and precipitation. CP 1, the eastern gulf low, is typically associated with substantial positive deviations of chlorophyll off the west coast of Florida, particularly near its peak occurrence times of August–October (when this pattern is indicative of tropical systems) and February and March (midlatitude cyclones). The two other cyclonic patterns, CPs 2 and 3, which are transition–winter and winter dominant, respectively, also are broadly associated with increased chlorophyll levels across the region of interest.

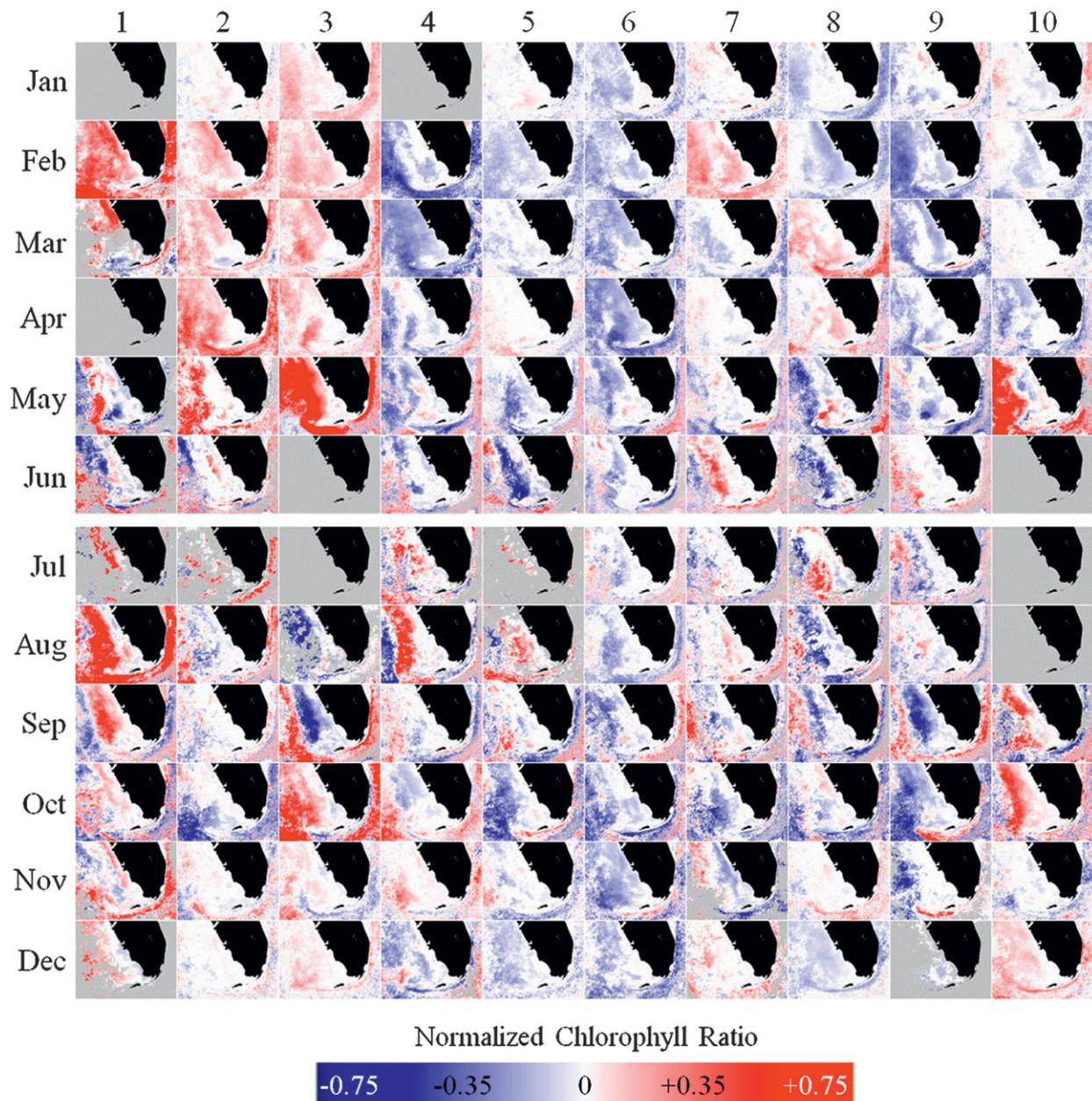


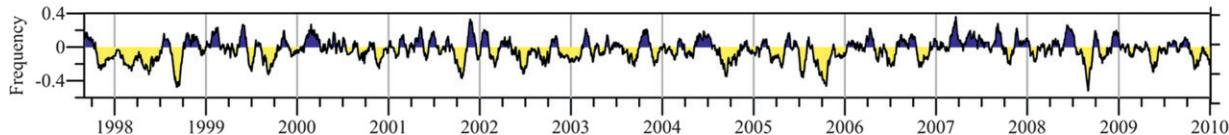
FIG. 4. SeaWiFS climatological chlorophyll associations with (left to right) CPs (1–10) calculated as the ratio of the mean of 5-day values on dates when each CP occurred to the (top to bottom) climatological mean monthly value for the 10-yr period. The figure enables visualization of positive (red) and negative (blue) chlorophyll deviation associated with each CP. Gray areas indicate no data are available (generally because of cloud cover).

In comparison, CPs 4–6 and 9, which are generally associated with anticyclonic conditions across the broader region, are associated with below-normal chlorophyll levels through much of the year. CPs 6 and 9, both summer-dominant patterns affiliated with a weak pressure gradient and a broad Bermuda high, show the most consistent month-to-month negative association. CP 4, spring dominant, and CP 5, cold-season dominant, both associated

with a cold-core anticyclone to the northeast of the region, are also associated with negative chlorophyll anomalies.

With the clear association between most cyclonic (anticyclonic) CPs and higher (lower) levels of chlorophyll, further tests assessed whether anomalous chlorophyll conditions could be associated with anomalous frequency of the CPAs that were discussed above. Time series of 29-day cyclonic and anticyclonic CPA anomalies and

Anticyclonic Patterns (4,5,6,9)



Cyclonic Patterns (1,2,3)

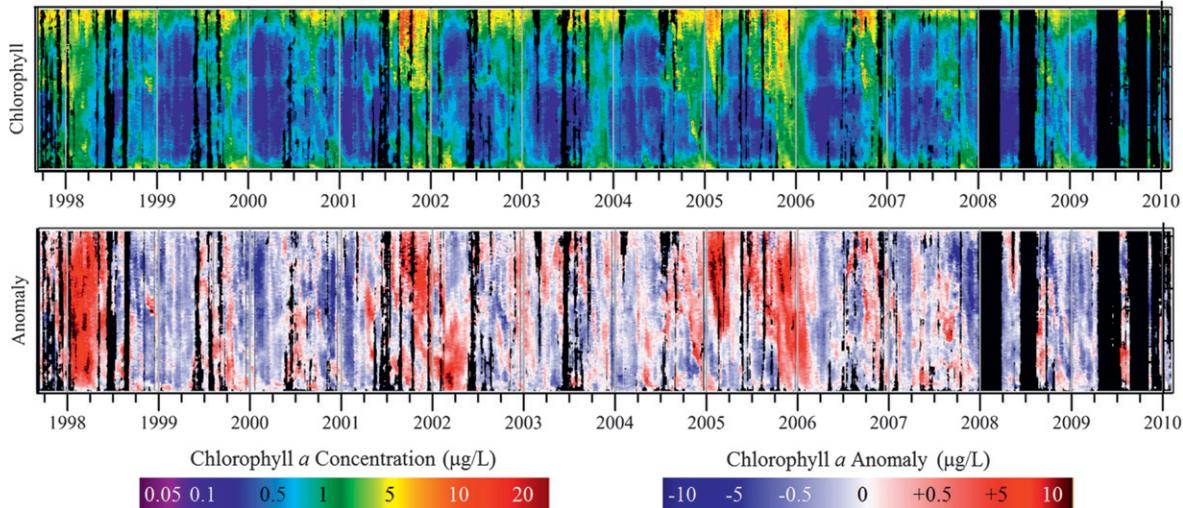
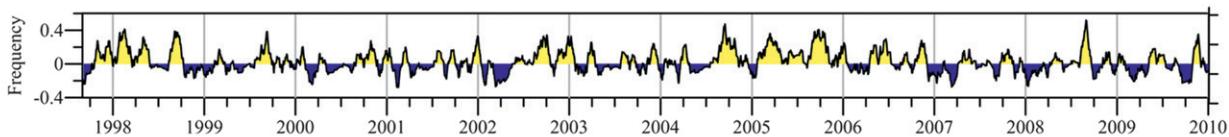


FIG. 5. Hovmöller plot of (third row) chlorophyll values with (fourth row) time series of anomalous frequency of the two CPAs: (top row) anticyclonic patterns and (second row) cyclonic patterns.

chlorophyll reveal peaks and dips in anomalous frequencies coincident with absolute and anomalous chlorophyll along the north–south transect in more detail (Fig. 5). As expected, heightened periods of cyclone development and storminess are revealed in positive deviations of the cyclonic CPA frequency, especially during winter and spring 1997/98, autumns 2001 and 2004, and autumn–winter of 2005/06. Of particular interest are the peaks associated with late summer–fall cyclones that traversed the area, including tropical storm Gabrielle (2001), Hurricane Charley and Tropical Depression Ivan (2004), and Hurricanes Katrina and Rita and Tropical Storm Wilma (2005). Also apparent is the interannual variability in wintertime cyclone activity that can be associated with El Niño–Southern Oscillation (Eichler and Higgins 2006); this association may be responsible for the active periods of 1997–98 and the more tranquil periods during winter–spring 1999/2000 and 2008/09 where cyclone activity, storminess, and chlorophyll were notably diminished, and supported by regional observation (H. O. Briceño 2012, personal communication).

Significant ($p < 0.05$) relationships between CPA anomalies and chlorophyll anomalies are observed across much of the transect. On an annual basis, there is a statistically significant correlation between both aggregates and anomalous chlorophyll values from roughly 25.3°N northward, peaking in the waters adjacent to Tampa Bay. South of 25°N, this correlation gradually approaches zero. Positive deviations in cyclonic frequency, relative to the time of year, are associated with positive chlorophyll anomalies; while positive deviations in anticyclonic frequency are associated with below-normal chlorophyll.

On a seasonal basis, the most significant overall relationships are observed during spring, with the association between cyclonic (anticyclonic) frequency anomalies and increased (decreased) chlorophyll again strongest in the vicinity of Tampa Bay, and decreasing southward (Fig. 6). While a general inverse relationship is seen between the two aggregates, a somewhat different pattern emerges in winter, when an increased frequency of cyclonic patterns is associated with statistically significant

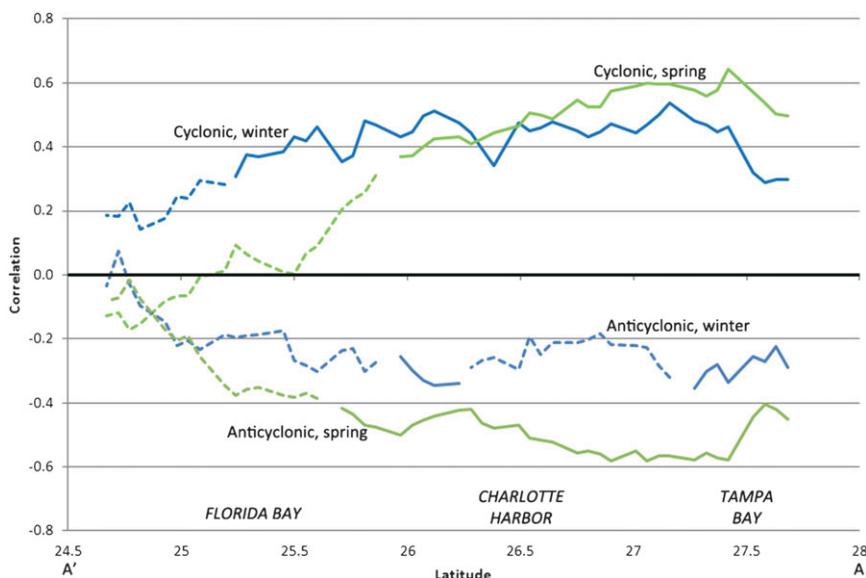


FIG. 6. Correlation coefficient between anomalous frequency of CPA and anomalous chlorophyll value for the transect shown in Fig. 2. Correlations that are statistically significant ($p < 0.05$) are illustrated with a solid line; insignificant correlations are shown with a dashed line. Only winter and spring are shown, as summer and autumn had almost no statistically significant results: (top) cyclonic and (bottom) anticyclonic pattern.

increases in chlorophyll, but anticyclonic patterns have a weaker association. Despite high-profile weather events such as hurricanes, the circulation–chlorophyll relationship is much weaker in summer and autumn; the correlations are generally in the same direction as the other seasons, although at much lower, and in most cases, statistically insignificant, levels.

Chlorophyll response scenarios based on the level of cyclonic and anticyclonic CPA frequency deviation is shown in the composited imagery in Fig. 7. Composited chlorophyll ratio maps yield consistent yet opposing sign relationships between CPA anomalous frequencies greater than and less than the 75th and 25th percentiles, and monthly chlorophyll response above or below mean conditions. In other words, when cyclonic anomalous frequencies increased above the 75th percentile over the distribution, chlorophyll patterns display widespread positive response (above mean conditions), irrespective of month. Conversely, a negative response is evident when cyclonic anomalous frequencies decreased below the 25th percentiles over the distribution. A similar but opposing sign relationship is evident with the anticyclonic anomalous frequencies and chlorophyll response, but with slightly more consistent and widespread pattern responses. The pattern responses are generally very stable over seasonal cycles with more positive chlorophyll responses nearshore during the winter upwelling season, most reflective in the cyclonic CPA

(Fig. 7), and more widespread (Gulf of Mexico and shelf areas) during late winter and spring in the anticyclonic CPA.

4. Discussion

Documented cases of synoptic forcing corresponding with upwelling–downwelling events and resulting in changes in distribution patterns of chlorophyll, particulate and dissolved matter, and other bio-optical properties on the shelf are well established in the region (Walsh et al. 2003; Weisberg et al. 2004; Liu and Weisberg 2005; Ault 2006; Hu and Müller-Karger 2007; Conmy 2008). CPs 1, 2, and 3 are associated with storminess, frontal passages, and enhanced pressure gradients hinting at a circulation-induced response in chlorophyll. In particular, CP 3 generally exhibits an enhanced north–south flow structure and could strengthen upwelling-related processes and mixing along the shelf. Regarding cyclones, specific cases of increased cyclonic activity, frontal passage, and/or upwelling events are well represented in the time series. The year of 1998 and autumns of 2004 and 2005 were especially active (Walsh et al. 2003; Weisberg and He 2003; Briceño and Boyer 2010) and may be connected to periods of increased hurricane activity or El Niño winters that are associated with a more active jet stream in the region (Eichler and Higgins 2006). During periods of hurricane passage, coincident were increased

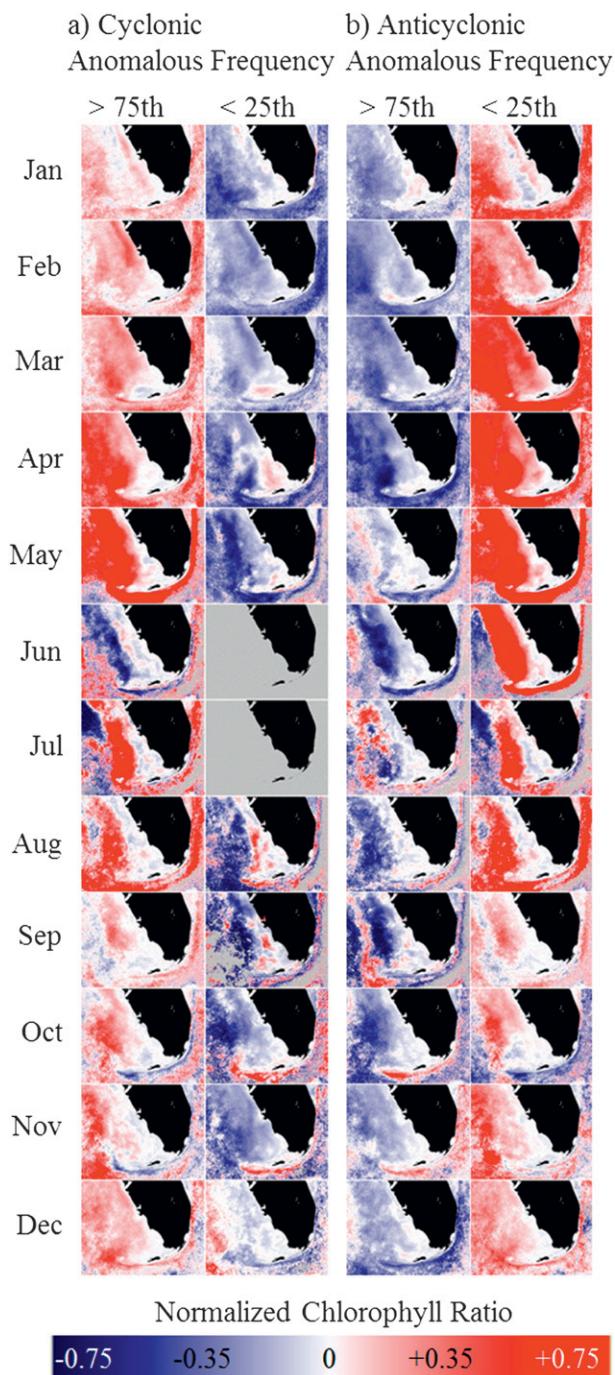


FIG. 7. SeaWiFS climatological chlorophyll response scenarios based on level of frequency deviation of (a) cyclonic and (b) anticyclonic CPAs. Chlorophyll deviation was calculated as the ratio of the mean of the 5-day values for dates that matched above and below the 75th and 25th percentiles for the anomalous frequency distribution, to the 5-day long-term running monthly mean value. The figure enables visualization of positive (red) and negative (blue) chlorophyll response associated with CPA frequency. Gray areas indicate no data are available (generally because of cloud cover).

frequencies of CP 1 and 2 during or before passage, and these years exhibited increased chlorophyll concentrations. Extended periods of elevated particle distributions (and chlorophyll) are speculated to be the result of excessive rainfall events (tropical and extratropical cyclones), coupled with offshore circulation and transport.

Variability in chlorophyll along the west Florida shelf and Florida Keys is most likely driven by a combination of weather-related factors including, but not limited to, wind-driven resuspension events, upwelling–downwelling, and excessive rainfall events initializing a dramatic or latent algal bloom response. Multiple studies have attributed annual reinforcement of algal blooms in the region, including red tide *Karenia brevis* blooms, to increased nutrient loadings from high rainfall, riverine–groundwater discharge, and hurricanes (Okey et al. 2004; Hu et al. 2006; Vargo 2009), resuspension and water column mixing from storm and wind events, and upwelling-related processes (Lohrenz et al. 1999; Weisberg et al. 2004). The triggering mechanisms to algal stimulation, and thus chlorophyll concentration, are impossible to discern from this investigation. However, because chlorophyll was significantly correlated with cyclonic (and anticyclonic) CPA anomalous frequencies, these weather patterns may act in combination to distribute and/or redistribute nutrients and other particles to initiate a chlorophyll response and then reinforce it, as seen in the prolonged anomalies after primary peaks (Fig. 5). Although it is an inherent assumption that within-pattern variability in a synoptic classification scheme is “acceptable” for analysis (Yarnal 1993), it is clear that extreme events (in particular for this study, hurricanes) will get aggregated into CPs that also contain much weaker events. The results of this study suggest that extreme events and less-extreme systems may elicit similar responses in chlorophyll, although further research is needed.

In summer and early autumn, intermittent storm systems including tropical and extratropical cyclones are known for widespread impacts to the region (Briceño and Boyer 2010), and cyclones are represented well in the cyclonic and anticyclonic anomalous CPA frequencies during the active tropical seasons of 2001, 2004, and 2005. During winter and early spring, it is speculated that cyclonic patterns correspond with seasonal cycles and mechanisms for controlling coastal transport, which influence wind stress, upwelling–downwelling-favorable circulation, nutrient release from runoff and/or resuspended sediments, and perhaps surface chlorophyll production, especially for the northern part of the study area, where upwelling is more prevalent (Yang et al. 1999). The decreased correlation between cyclonic CPA

frequencies and chlorophyll response moving south from Tampa toward the Florida Keys would support this premise. It is also speculated that the combination of both cyclonic and anticyclonic CPAs influence nutrients and algal particle distribution/redistribution in shelf waters, and that increased frequency and duration of cyclonic (anticyclonic) patterns act to enhance (diminish) chlorophyll signals at the surface. Since frequency deviations of cyclonic and anticyclonic CPAs at the upper and lower quartile ranges revealed clear differences in chlorophyll deviation (Fig. 7), this does suggest that circulation patterns affect chlorophyll levels in combination (not just with singular cyclone passages) over monthly intervals.

This study provides insights on the utility of synoptics and derived time series for assessing coastal water quality-related change in south Florida. The development of consistent time series of atmospheric circulation patterns helped explain deviations in satellite ocean color chlorophyll and holds particular relevance when assessing the complex combinations of factors that influence phytoplankton growth, abundance and distribution. We believe the use of synoptic climatological methods in ocean research is fairly unexplored, and we argue that further research is clearly justified. Because weather and circulation play a significant role in ecosystem-level responses, as is the case for chlorophyll, future work is clearly needed to evaluate the potential for weather types or circulation patterns as prospective short-term indicators of ecosystem-level change. Given the connection between atmospheric teleconnections and circulation patterns (e.g., Eichler and Higgins 2006), the use of teleconnections for seasonal predictions of anomalous circulation pattern frequency should be assessed as well. Moreover, the utilization of these relationships with general circulation model output of projected conditions may serve as a long-term forecasting tool as well, for future water quality conditions in this ecologically and economically important coastal region.

Developing consistent, integrated procedures for modeling ecosystem status and change is an area where this work specifically applies, as it allows for the quantification of responses directly related to regional weather phenomena, with focus on specific domains over specific temporal intervals. We argue that expansion of this work would provide the needed resolution to help facilitate improved use of in situ and remotely sensed observational monitoring and regional reanalysis data, and will promote the development of new regional science and management collaborations across governmental and nongovernmental agencies and institutions focused on technical learning, communication, and outreach.

5. Conclusions

The synoptic climatological approach developed herein shows that atmospheric circulation, and the associated frequency and duration of circulation patterns, is significantly linked to ecosystem-level response. Emphasis was on climatological events and documented cases in the literature relevant for understanding the mechanisms to chlorophyll response, and for modeling driver-response relationships. We suggest that synoptic climatological methods have particular relevance in ecological applications such as algal bloom prediction, coastal water quality tracking and monitoring, and habitat (e.g., coral, sea grass) impact monitoring. The circulation pattern aggregates provided a means to effectively relate and mechanistically describe the drivers attributing to chlorophyll changes in the region, as evidenced by the significant correlation between CPA frequencies and chlorophyll response.

Through this study we showed that synoptic weather conditions are inherently linked to chlorophyll levels, and derived weather classifications are likely reliable determinants in the assessment of coastal and estuarine water quality, ecological status, and change. Chlorophyll indicators are especially relevant in south Florida coastal systems, where water quality and nutrient pollution are of significant concern (Florida Oceans and Coastal Council 2009; FDEP 2009; USEPA 2009). The synoptic-to-satellite technique accounted for both the temporal and spatial aspects in weather and water characteristics, providing a favorable perspective to assess change from reference conditions. Planned follow-up research will include additional testing of these methods with other parameters known to be associated with ecosystem health and change, including turbidity, light attenuation K_d , and sea surface temperature. Research will also assess the role of specific CP transitions, as well as persistence, in affecting these water quality variables.

Anticipating ecosystem-level change through an automation of synoptic types and water quality response would support proactive management decisions in coastal nutrient and sediment management, in watershed restoration, assessing fisheries impacts, and the tourism industry (diving-fishing), where knowledge of past and future trends in weather conditions and synoptic forcing is critical. Likelihood estimates of both synoptic types and environmental change indicators would provide much-needed information to federal- and state-level nutrient and watershed restoration managers and other end users about the exogenous yet pervasive effects of weather on ecosystems, and should be an important consideration in any coastal adaptive management strategy.

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