Anomalous marine biophysical conditions due to 2016 and 2017 wind and flooding events in the Northeastern Gulf of Mexico

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ABSTRACT

Ocean observing satellites and models reveal anomalous surface properties associated with the 2016 Bonnet Carré Spillway opening and a 2016 Flower Garden Banks mortality event. Marine bio-optical and physical processes in northeastern Gulf of Mexico are largely driven by river discharge and wind-driven circulation. Satellite observations and regional ocean model output were used to evaluate these processes and their interactions over large spatial areas. Climatology of Visible Infrared Imaging Radiometer Suite (VIIRS) ocean color imagery and Navy Coastal Ocean Model American Seas (AMSEAS) output for the region were generated to explore temporal variability and detect anomalous events. Here we present the 2016 and 2017 time series of 1.) 8-day 750 m resolution VIIRS observations for chlorophyll-a, diffuse attenuation coefficient, and euphotic depth; and 2.) 8-day 3 km AMSEAS output for surface temperature, salinity and currents. From these time series, we derive temporal anomalies for each parameter. Results from longer term anomalies show elevated ocean color values across the region following a January 2016 river flooding event, and Bonnet Carré Spillway opening, that persist through summer months. The elevated values are compared with river discharge rates and known events (i.e. July and October 2016 Flower Garden Banks mortality), revealing the impacts of the flooding to the region. Results from shorter term anomalies highlight the stages and migration of specific impacts, such as possible upwelling at Flower Garden Banks (January 2016) observed in currents and chlorophyll-a fields.

Keywords: Remote Sensing, Anomalies, Gulf of Mexico, Ocean Color, Mississippi River, Bonnet Carré, Flower Garden Banks

1. INTRODUCTION

The Northern Gulf of Mexico (Northern Gulf) is divided into eastern and western regions by the Birdfoot Delta of the Mississippi River. On average the Mississippi River delivers 13,000 m^3 of freshwater to the Northern Gulf(1,2) every second, although discharge volume varies along a seasonal pattern(1). Wind-driven alongshore currents typically direct riverine waters westward October – May and eastward June – September(1,2). The riverine waters affect bio-optical patterns, and therefore ecosystems, by bringing particulates, nutrients and warm buoyant freshwater to the shelf(2). As primary producers in marine waters, phytoplankton are directly impacted by riverine input. Phytoplankton biomass and distribution can be estimated via chlorophyll algorithms utilizing water leaving radiance measured by satellite ocean color sensors(3,4).

Bio-optical observations (chlorophyll, total absorption and the diffuse attenuation coefficient) and anomalies derived from the Visible Infrared Imaging Radiometer Suite (VIIRS) and circulation model forecasts from the American Seas Model (AMSEAS) of surface temperature and salinity were used to evaluate two wind and flood related events in the Northern Gulf of Mexico: 1.) the 2016 Bonnet Carré Spillway opening and 2.) the 2016 Flower Garden Banks mortality event. These events are perturbations to the typical local marine system in that they are episodic, not seasonal, and therefore provide insight to regional sensitivity to oceanic events. For each event, observations were compared with climatological values to assess the relative impact of the events to typical seasonal patterns and the scale of spatial impact.

In January of 2016, the Bonnet Carré Spillway was opened in response to elevated Mississippi River discharge resulting from heavy rain along its drainage basin(5). Built in 1931, the spillway is designed to mitigate Mississippi River flooding of New Orleans by diverting water from the main channel eastward to Lake Ponchartrain(5,6). Opening the spillway leads to river water influx east of the Birdfoot Delta, the main discharge is typically the west side of the delta(6). While the eastern side of the delta, the Mississippi Bight (Figure 1), is frequently impacted by Mississippi River waters, the opening of the spillway allowed direct entry to the bight from the northwest rather than the southeast. This altered entry point was expected to cause changes in freshwater, nutrient and particulate concentrations within the bight, and resultant changes in satellite-viewed ocean color. The 2016 spillway opening was the 11th opening in 85 years and was the first winter opening in its history(5). These conditions suggest that the effects to bight waters would be anomalous both in comparison with climatological conditions and with near-preceding conditions.

Near the shelfbreak of the northwestern Gulf, divers reported unusual cloudy water conditions at the East Flower Garden Bank on July 25, 2016(7). The East and West Flower Garden Banks are deep water coral reefs south of Texas (Figure 1)(7,8). These reefs were granted Marine Sanctuary status by NOAA and are monitored by a team of managers and scientists(8). Marine Sanctuary scientists investigated the reports of cloudy conditions and found a mortality event at Buoy 4 of the East Flower Garden Bank(7). The event was severe yet localized and was determined to have occurred within a matter of days(7). While a cause has not been determined, researchers from multiple institutions have studied the mortality and determined that the event was not pollutant driven. Ocean color satellite observations do not have the fine temporal or spatial resolution to pinpoint a short term, small areal mortality event at Flower Garden Banks, yet it was anticipated that environmental changes occurring before or during the die-off would be evident in the satellite record. Further, the conditions leading to such an event were hypothesized to show as perturbations or anomalies to the typical marine condition for the region.

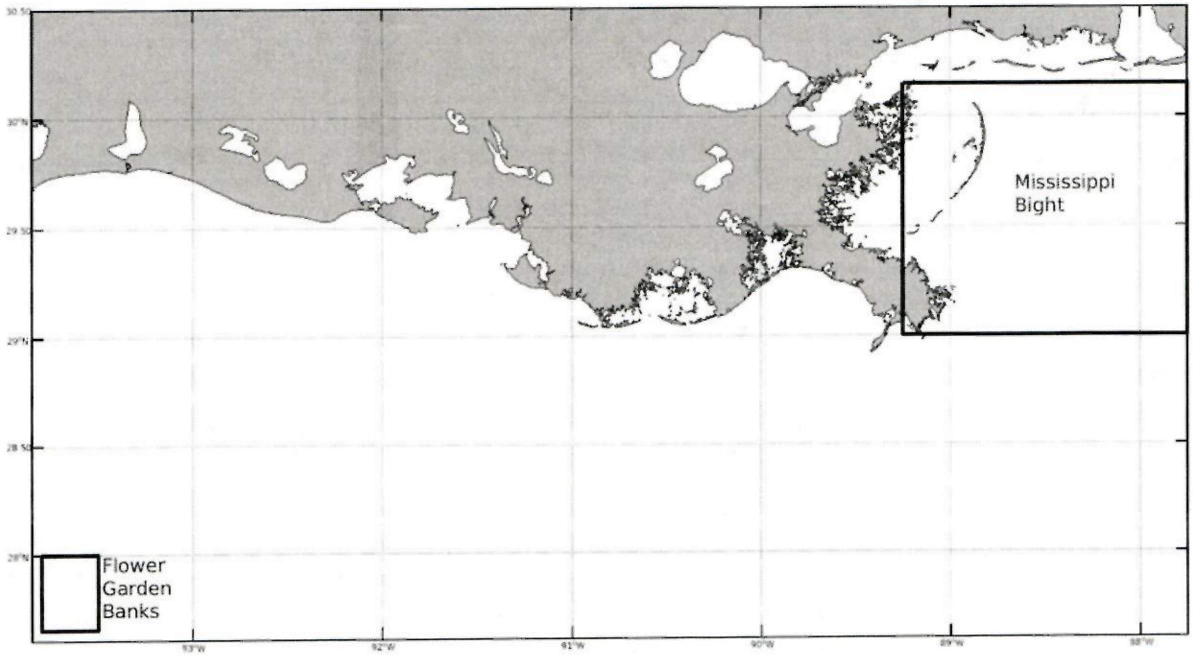

Figure 1. Northern Gulf of Mexico study region map. The region marked Mississippi Bight was used for the Bonnet Carré Spillway analysis. The region marked Flower Garden Banks was used for the East Flower Garden Banks mortality analysis.

Here we present findings from our investigation of these events. In section 2, a brief overview of the satellite and model data is provided, with an explanation of processing methods and anomaly calculations. In section 3, the results of each event investigation are presented with mapped plots for visualization of spatial variability within the regions of each event. In section 4, we discuss the anomalous conditions associated with these events and how effective these methods are in monitoring such events and impacts.

2. DATA AND METHODS

2.1 Satellite Data

Daily sensor data was downloaded from NOAA Class for VIIRS aboard the Suomi NPP Satellite. Atmospheric correction was applied to water leaving radiance at 410, 443, 486, 551, 671, 745 and 865 nm before deriving bio-optical properties using APS (v5.1), derived from NASA's L2Gen program(11). The properties used were chlorophyll, total absorption at 443 nm and the diffuse attenuation coefficient of photosynthetically available radiation at 486 nm (Kd)(12). Resolution was daily, 750 m for all ocean color properties.

Chlorophyll algorithms can be influenced by colored dissolved organic material (CDOM) and detritus in optically complex waters, such as shelf and riverine waters(8). To account for the effect of these organic materials on the chlorophyll estimate, the relationship of chlorophyll to total absorption(13) was explored. Additionally, to determine the turbidity of waters, the Kd product was used as a proxy for any materials attenuating light with depth. All properties were temporally averaged to generate 8-day means, 64-day means and 64-day standard deviations.

2.2 Model Output

Model output of physical properties for the Northern Gulf were obtained from the Navy Research Laboratory and the National Centers for Environmental Information. Modeled currents, temperature and salinity from the AMSEAS(14) model were downloaded as 3-hour estimates at 3 km resolution. Aggregation and temporal averaging of model products was performed using in-house software to generate daily means, 8-day means, 64-day means and 64-day standard deviations.

2.3 Methods

To detect events and event perturbations to typical patterns, a time series and climatology of each property was developed at each pixel (satellite) or node (model). Data for each study region was aggregated to consider regional seasonal patterns and event-associated anomalies. Two types of anomaly were used for this study, long term (4-year) and recent change(9) (2-month). To determine the 4-year anomaly, the 4-year climatology was subtracted from the week of interest (i_w). This anomaly can be used evaluate how typical any week of interest is compared with the respective corresponding climatological week.

$$A_w = i_w - C_w$$

where

$$i_w = \frac{1}{p} \sum_{v=1}^{p} x_v$$

(p is the number of pixels included in the study region, and x_v is the property value at a given pixel)

and

$$C_w = \frac{1}{n} \sum_{y=1}^{n} i_{w_y}$$

(n is the number of years averaged, and i_{wy} is the week of interest in a given year)

The recent mean condition is the 64-day mean preceding the week of interest, with a 16-day lag. The recent change anomaly is calculated by subtracting the recent mean condition from the week of interest. This anomaly provides insight to ongoing change within a study region.

$$RC_w = i_w - RMC$$

where

$$RMC = \frac{1}{8}\sum_{r=3}^{10} i_r$$

(i_r is the study area spatial mean of the property for a given week)

3. RESULTS

3.1 Bonnet Carré Spillway

The effects of the 2016 Bonnet Carré Spillway opening to the ecosystems of the Mississippi Bight were investigated by the distribution of chlorophyll-enriched waters for the first 64 days of 2016. Maps of the distribution before, during and after the closing of the spillway show the south-eastward progression of the chlorophyll-enriched front across the Mississippi Bight (Figure 2 (a, b, c)). The 4-year anomaly shows an increasing amplitude of deviation and spatial coverage as the event proceeds (Figure 2 (d, e, f)). The anomaly shows that while the front is seen to spread southeastward in the weeks preceding the closing of the spillway, only waters near land measure at higher than typical chlorophyll values. The recent change depicts the spatial variability of ongoing chlorophyll elevation relative to previous weeks, allowing the frontal productive water movement and/or phytoplankton growth to be tracked (Figure 2 (g, h, i)). The progression shows the offshore migration of chlorophyll-enriched waters following the closing of the spillway.

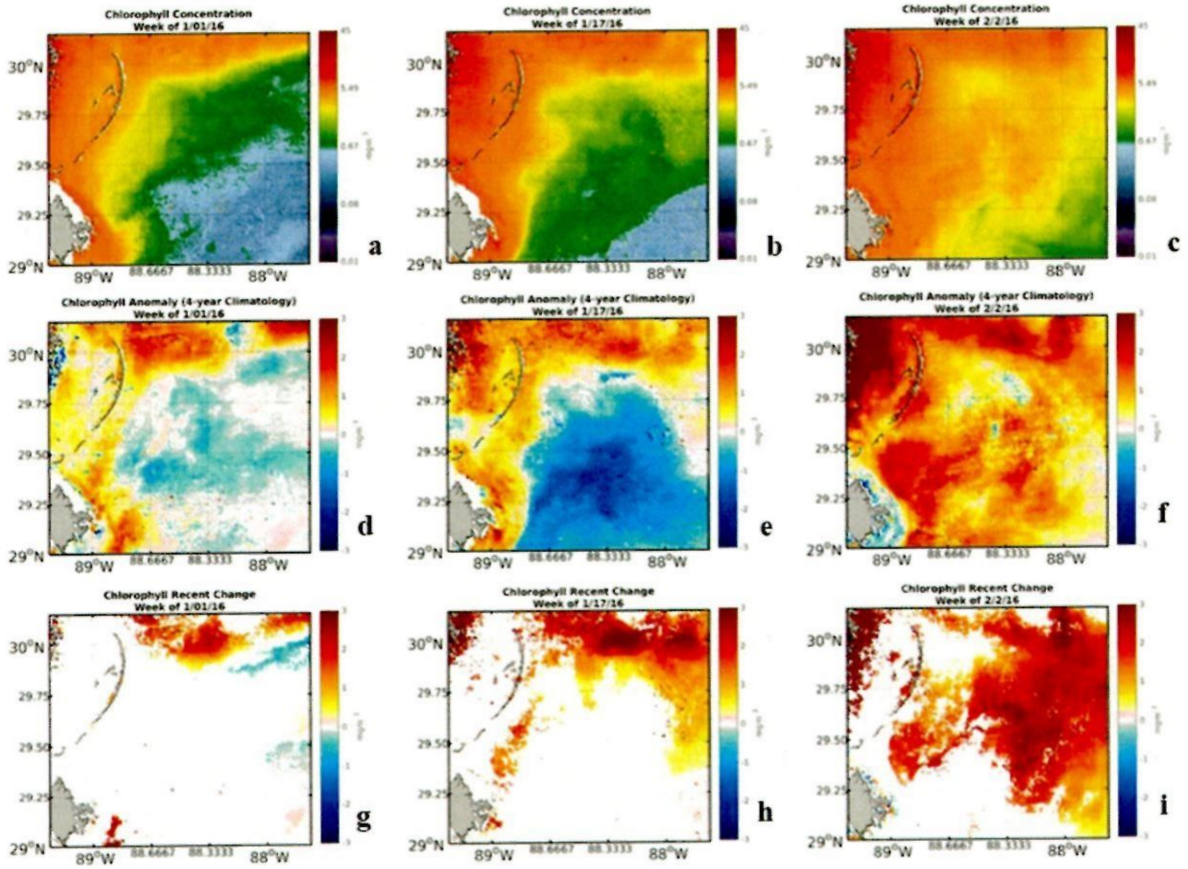

Figure 2. Distribution of chlorophyll enriched waters associated with the 2016 Bonnet Carré Spillway opening. Mean weekly chlorophyll before spillway opening (a), at maximum outflow (b) and after closing (c). The 4-year anomaly before the spillway opening (d), at maximum outflow (e) and after closing (f). Recent Change before the spill way opening (g), at maximum outflow (h) and after the closing (i).

The pixel values for the Mississippi Bight were averaged to generate a 4-year time series of observed chlorophyll and chlorophyll anomaly (Figure 3). The climatological chlorophyll values for the weeks associated with the event ranged from 0.53 – 0.66 mgm^{-3}. The spatially averaged chlorophyll reached ~ 60 % higher than typical at 1.0 mgm^{-3} following the flood event in 2016. To account for the limited years available to generate the climatology (4 years), and potential skewing by any one year (25 % of total observations), the range of values was also calculated without the year 2016. However, this did not considerably alter the range (chlorophyll = 0.53 – 0.65 mgm^{-3}). Considering the full 4-year time series of observed chlorophyll indicated that the spillway opening was the second highest chlorophyll value for the region. the highest averaged chlorophyll was 1.41 mgm^{-3}, and all other peaks were below 1.0 mgm^{-3}. Similarly, the anomaly time series showed that the spillway opening was the second highest positive anomaly in the 4-year record. The positive anomaly continued for 6 months following the event, which was the longest positive anomaly on record, suggesting that the opening had a potentially long-term impact to regional conditions.

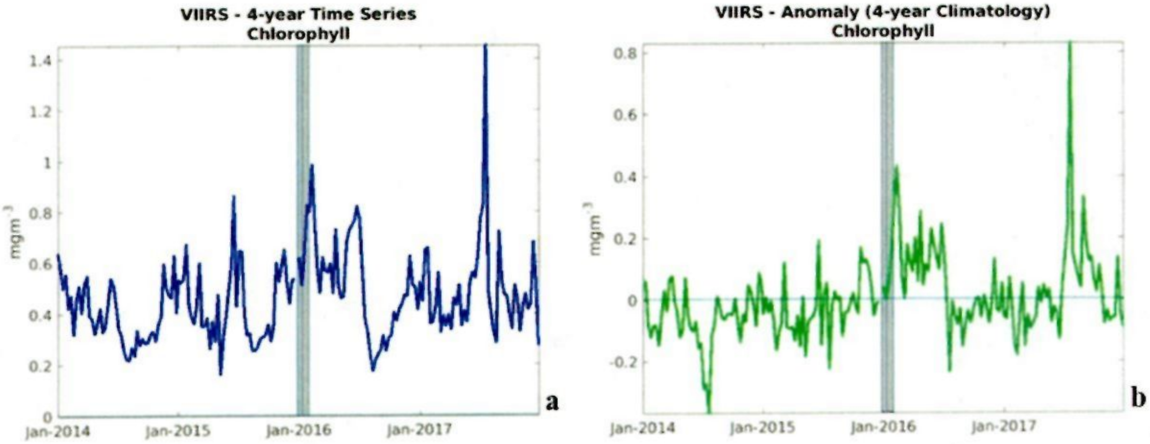

Figure 3. Mississippi Bight 4-year time series of observed chlorophyll and chlorophyll anomaly. The average chlorophyll across the bight for each 8-day period of 2014-2017 (a) shows the spillway opening (gray shading) preceding the second highest regional chlorophyll for the 4-year time series. The anomaly time series (b) reveals that the peak was both anomalous in amplitude and extent. The climatological chlorophyll at each week is denoted by the horizontal line. The spillway opening (gray shading) precedes the longest period of positive chlorophyll anomaly observed in the region over the 4-year time series (6 months).

The positive anomaly peak associated with the spillway opening was seen during a period seasonally low Mississippi River discharge (Figure 4). The 6-month positive anomaly condition following the opening spanned both low and high seasonal discharge rates.

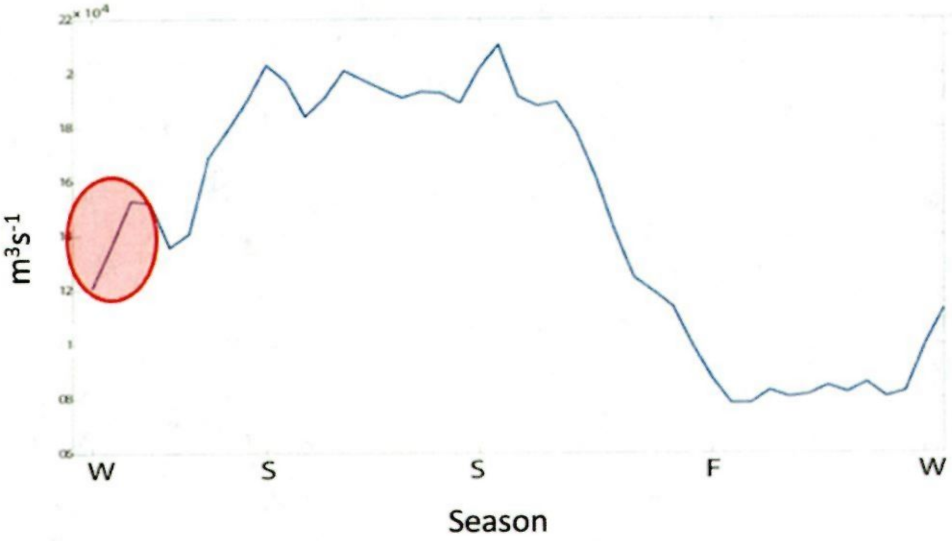

Figure 4. Seasonal Discharge of the Mississippi River at USGS Baton Rouge station(7). 11-year (2008-2018) climatology of discharge rates shows seasonality of flow (blue line). The period of the Mississippi River flood event and Bonnet Carré Spillway opening is highlighted in red. (data collected for

The derived chlorophyll product is an estimate of the absorption by phytoplankton. Satellite chlorophyll algorithms are optimized for clear, oligotrophic water where the contributions to absorption at determinant wavelengths are primarily made by phytoplankton. In considering the influx of optically complex waters to the shelf, the chlorophyll estimates would be expected to be imprecise due to presence of significant amounts of organic material and particulates. Because the total absorption at 443 nm (abs-443) includes absorption by phytoplankton, detritus and CDOM, the relationship between chlorophyll and total abs-443 was used to explore whether the contribution of phytoplankton to the abs-443 signal changed during the opening (Figure 5). In oligotrophic waters these properties would be strongly correlated due to the relatively high chlorophyll contribution to abs-443 in low-CDOM/detritus waters. A logarithmic regression was used to determine R^2 value as a determinate of correlation. The relationship between chlorophyll and abs-443 in the Mississippi Bight during the event strengthened from a climatological R^2 of 0.84 to an event R^2 of 0.91. Following the closing, when spillway waters would have moved out to the bight, the R^2 value fell to 0.69 from a climatological value of 0.79.

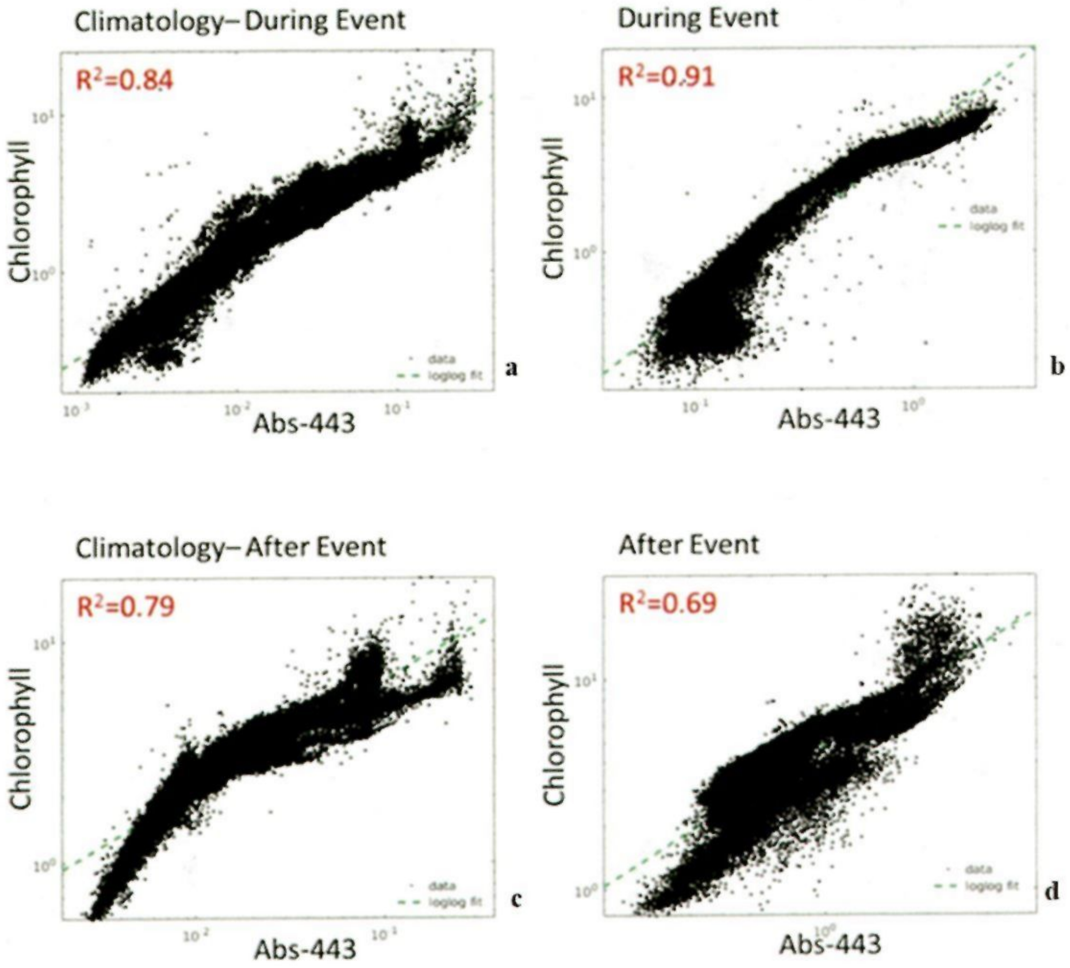

Figure 5. Chlorophyll v. Total Absorption at 443 nm associated with the 2016 Bonnet Carré Spillway opening. The typical relationship between chlorophyll and absorption in the Mississippi Bight at the time of the is shown (a) with an R^2 of 0.84. At the time of the opening the Mississippi Bight had a somewhat stronger chlorophyll-absorption R^2 of 0.91 (b). The week of the closing the R^2 is 0.69 (d), this is weaker than typical for this time period (c).

3.2 Flower Garden Banks

A 50 x 50 km region encompassing both East and West Flower Garden Banks was chosen to evaluate marine conditions before and during the reported mortality event. The distribution of chlorophyll in the selected region were mapped within a larger region to visualize the study area and influences from surrounding shelf and offshore water features (Figure 6). The 8-day chlorophyll distribution suggests coastal migration of chlorophyll-enriched waters to the study area. When compared with the climatological values (0.65 mgm^{-3}), the chlorophyll was not significantly elevated (0.67 mgm^{-3}). The recent change did indicate a slightly more positive chlorophyll value than the recent mean condition. When considering the recent change map in the context of surrounding waters, the elevated chlorophyll appears influenced by offshore circulation.

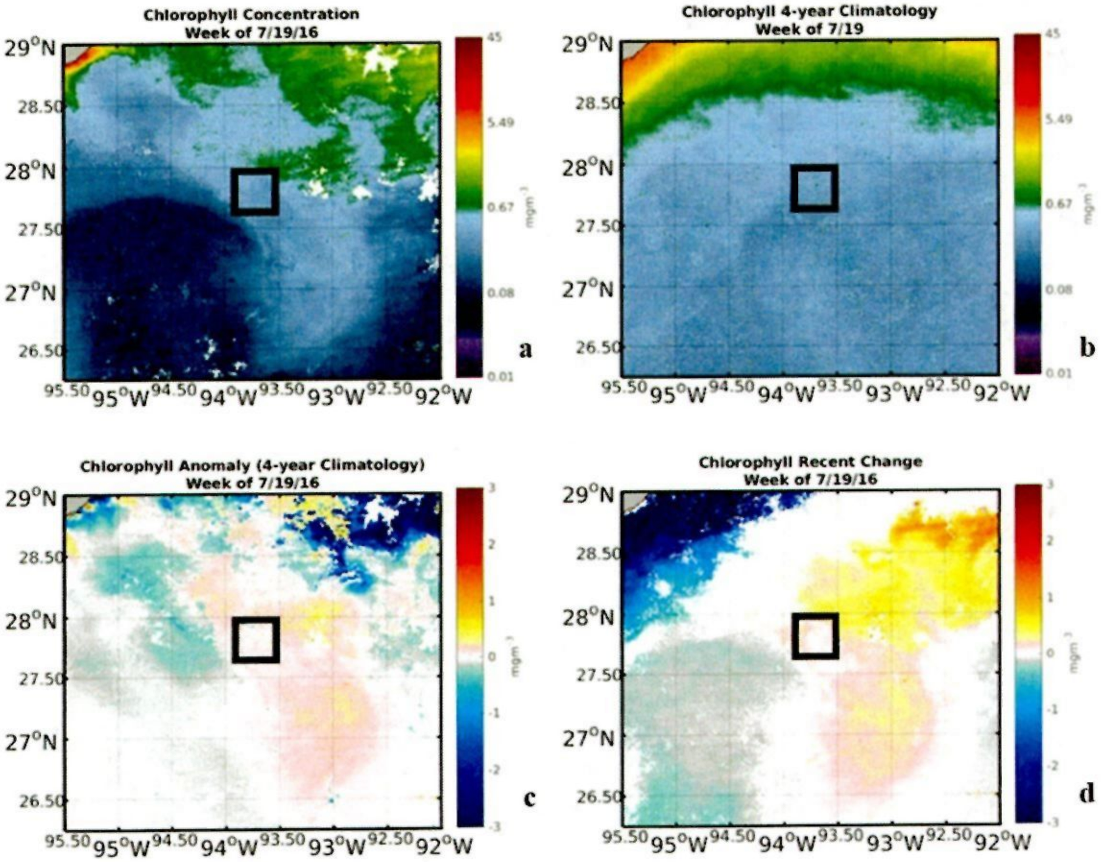

Figure 6. Chlorophyll observations associated with the 2016 East Flower Garden Banks mortality event. 8-day chlorophyll concentration (a), 8-week mean chlorophyll concentration (b), 4-year chlorophyll anomaly (c) and recent change in chlorophyll (d).

Considering the known localized nature of the event (radius of less than 250 meters), the 64-day standard deviation of chlorophyll derived during calculation of the recent mean condition was plotted to determine the homogeneity of chlorophyll variability across the study area (Figure 7). Maps of years 2013-2016 reveal that spatial variability and interannual variability are typically consistent with the exception of year 2016 near the area of the die-off. The localized increase in standard deviation seen in 2016 (3-5 mgm^{-3}) is an order of magnitude greater than other observed years.

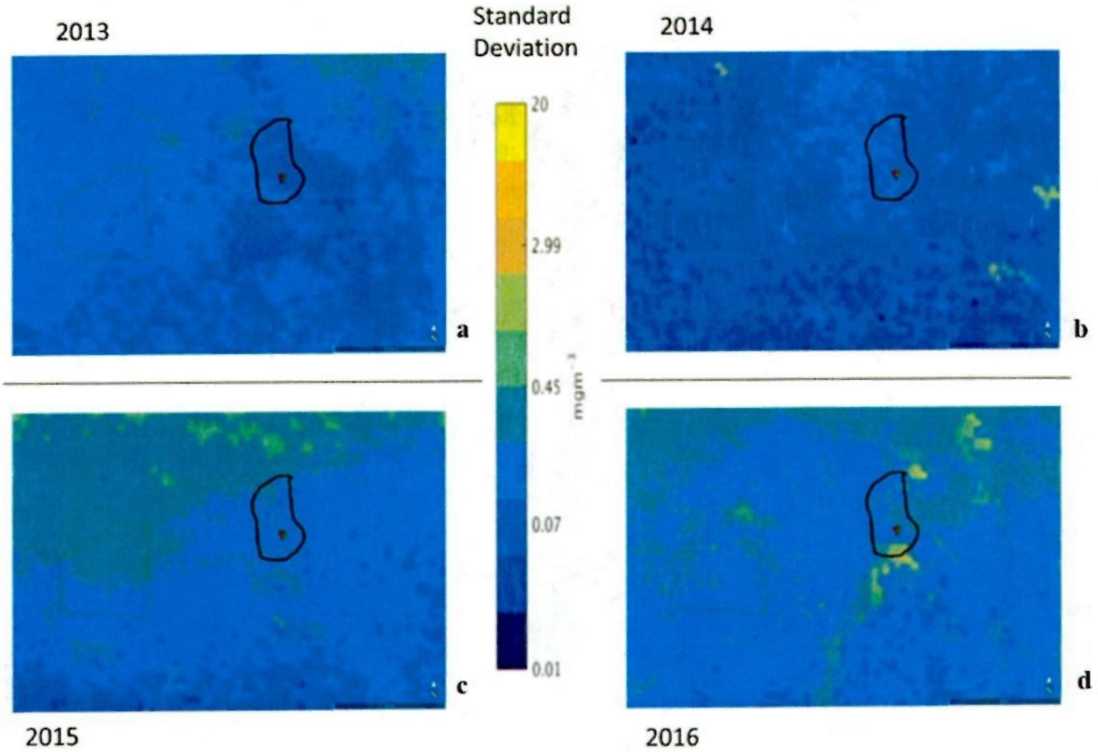

Figure 7. Standard deviation of chlorophyll at East Flower Garden Banks for June/July of 2013-2016. The temporal standard deviation of chlorophyll at each pixel for the eight 8-day time periods of June and July are shown for each year 2013 (a), 2014 (b), 2015 (c) and 2016 (d). A black line is used to delineate the East Flower Garden Banks boundary, and marker is located at the site of the mortality event.

To consider the effectiveness of chlorophyll as an indicator of changing condition in the region, the relationship of chlorophyll to abs-443 was determined using logarithmic regression (Figure 8). The relationship strength is expressed using R^2 value. The climatological relationship between chlorophyll and abs-443 was weak ($R^2 = 0.26$) for the study area during the time that the mortality was discovered. The relationship was much stronger during the event ($R^2 = 0.68$), however still not indicative of a strong chlorophyll contribution.

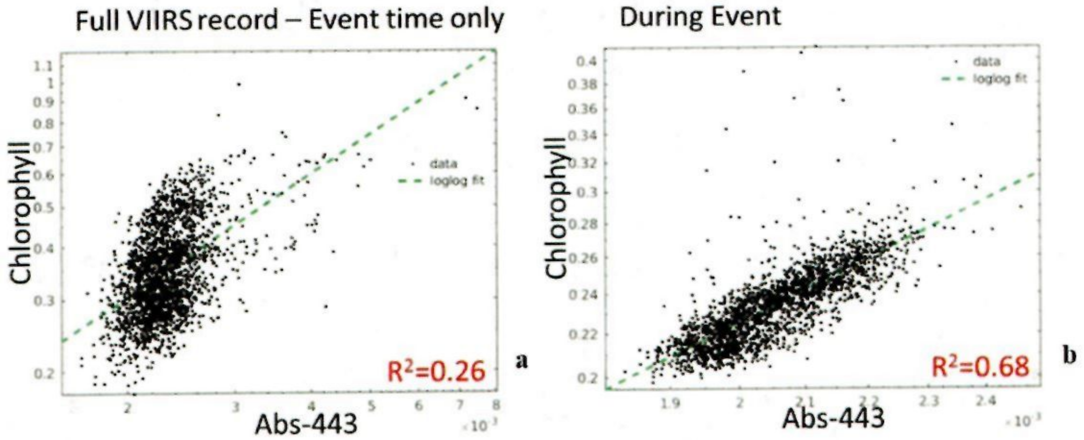

Figure 8. Chlorophyll v. Total Absorption at 443 nm associated with the 2016 East Flower Garden Banks Mortality Event. The climatological relationship between chlorophyll and absorption is shown (a) with an R^2 of 0.26. The week of the mortality detection, the much stronger chlorophyll-absorption relationship with an R^2 of 0.68 (b) was measured.

The strengthening of the chlorophyll to abs-443 relationship did suggest a change in water properties, and turbidity as a function of light attenuation was selected for evaluation (Kd). Kd was mapped for the study region and surrounding areas to visualize the turbidity associated with the mortality event (Figure 9a). The Kd map suggested localized elevated turbidity at the Flower Garden Banks. To determine the significance of the high turbidity to the region, the 2016 Kd within the study area was plotted against the climatological year, and the climatological year with 2016 omitted (Figure 9b). The plot shows that turbidity was elevated above climatological values for a period of 7 weeks leading to the event with a maximum turbidity level (Kd = 0.1 m^{-1}) in the week preceding the event was higher than expected values (Kd = 0.065 m^{-1}) for this time. The 4-year time series of the anomaly for Kd (Figure 9d) shows that positive anomaly of turbidity at the time of the mortality event was the third highest regional positive turbidity anomaly on record, and the most persistent positive anomaly from 2013-2017. The positive anomaly also occurs in summer, unlike other positive turbidity anomalies that occur in winter and early spring.

Also associated with the mortality event is a low salinity, cyclonic circulation feature (figure 9c). The feature is immediately northeast of an anticyclonic feature, suggesting a potential front or advective pathway near the Flower Garden Banks region in the weeks surrounding the event. This is consistent with the recent change chlorophyll patterns noted in Figure 6d.

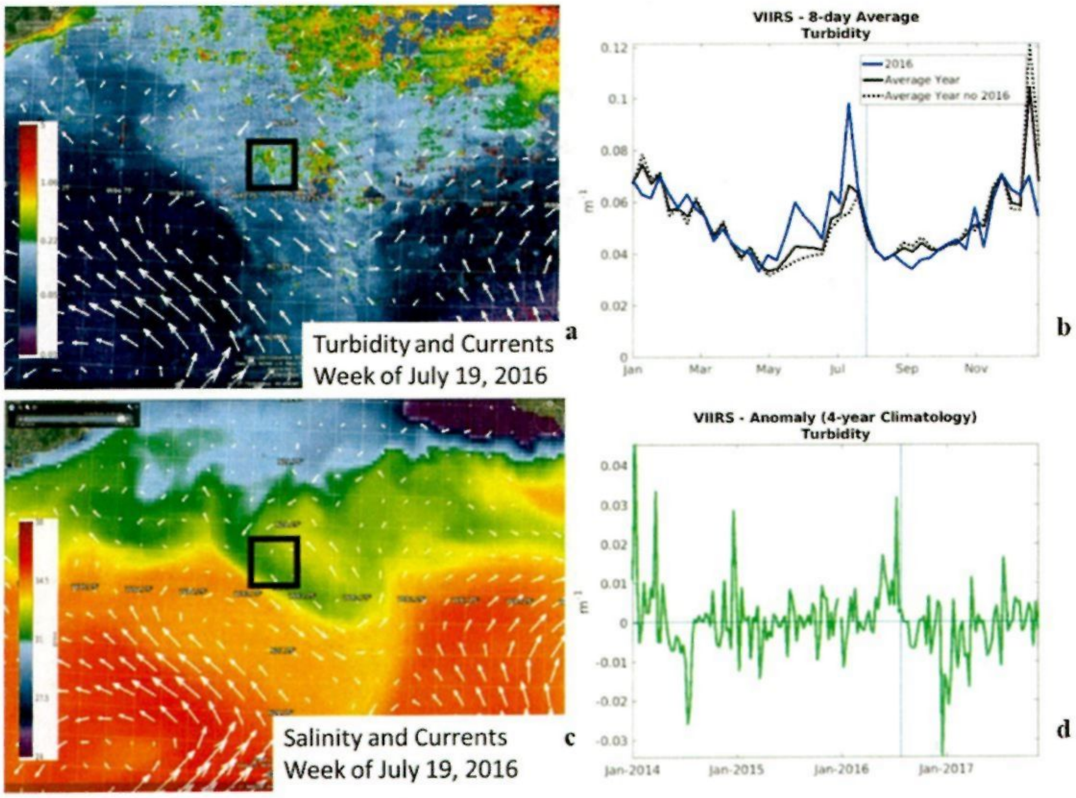

Figure 9. Turbidity and Salinity associated with the 2016 East Flower Garden Banks mortality event. The 8-day Kd composite (a) shows elevated turbidity at Flower Garden Banks (delineated with black box) preceding the mortality detection. A comparison of the regional turbidity 8-day time series (b) between 2016 (blue) and climatological turbidity (black) with the vertical line indicating the date of the mortality detection. The 4-year Kd anomaly time series (d) is shown with the date of detection identified by a vertical line and climatological turbidity by a horizontal line. The modeled salinity map (c) shows both a low salinity feature and a cyclonic rotation within the study area.

4. CONCLUSIONS

With proposed climate changes potentially increasing the frequency of flooding events, understanding the short- and long-term impacts of these events is critical for ecologically important adjacent waters. Remote sensing offers the opportunity to develop robust monitoring schemes for researchers and managers, providing synoptic large-scale observations at a fraction of the cost of ship-based measurements. Implications of changing water mass components detected following both events suggest the need for ecosystem impact studies in light of increased flooding frequency.

The Bonnet Carré Spillway has opened only 12 times in its history, yet the number of years between openings has decreased over time. It is essential for the fisheries and tourism-dependent waters of the Mississippi Bight that the effects of spillway waters to algal blooms, productivity and stratification be resolved. Here, we show that the flooding event necessitating the spillway opening did elevate chlorophyll concentrations above typical conditions. The elevation progressed across southeastward the bight. The recent change calculations provided the ability to monitor the variability of movement of the flood waters within the overall plume. The study was limited in its ability to distinguish Mississippi River waters from Bonnet Carré Spillway waters, both of which would potentially affect the bight.

Study of the conditions associated with the Flower Garden Banks mortality event point to the migration of coastal waters to the outer shelf, and subsequent advection due to offshore circulation. The increased turbidity may indicate the presence of local upwelling or particulate advection. Although a bloom was determined to be unlikely due to the low chlorophyll signal, the high standard deviation of chlorophyll and the strengthened relationship between chlorophyll and absorption may point to a short-lived phytoplankton bloom near the time of the mortality event.

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