Spatial and temporal characterization of cyanobacteria blooms in the Mississippi Sound and their relationship to the Bonnet Carré Spillway openings

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Abstract

During the spring and summer of 2019, an unprecedented cyanobacterial harmful algal bloom (cyanoHAB) was responsible for beach advisories on 25 beaches along the Mississippi Sound for over 3 months. Due to the preceding heavy rainfall and flooding within the Mississippi River watershed, for the first time in history, the Bonnet Carré Spillway (BCS) opened twice in one year during 2019. The coastal cyanoHAB coincided with the second BCS opening. The main objectives of this study were: (1) to investigate the potential for using the National Aeronautics and Space Administration (NASA) ocean color standard Cyanobacteria Index (CI_{cyano}) algorithm to characterize the spatial and temporal extent of the 2019 cyanoHAB; (2) to couple the CI_{cyano} data with river discharge, salinity, and modeled-wind data to study the conditions leading to the cyanoHAB and factors aiding the advection and persistence of the bloom within the Mississippi Sound, including a possible relationship to the BCS; (3) to further investigate the relationship

with the BCS by repeating the methods using data from 2018, which was a year when the BCS was opened but no evidence of cyanoHABs was reported along the Mississippi coast. Weekly means and monthly frequency CI_{cyano} images, river discharge, salinity, and modeled-wind data from February to September of 2018 and 2019 were analyzed, which coincide with three BCS openings. In March 2018, a cyanobacteria bloom was observed within Lake Pontchartrain coinciding with the BCS opening; however, the month-long bloom was contained to the lake. Two distinct cyanoHABs were observed in 2019 and both blooms were advected into the Mississippi Sound, and likely contributed to the 3-month-long beach water advisories of 2019 along the Mississippi coastline. From March to mid-July 2019, salinity at stations within the Mississippi Sound was consistently near zero indicating high levels of freshwater. During that time, winds were predominantly northwestward, preventing the BCS waters from flushing into the Mississippi Shelf and resulting in BCS waters remaining longer within the estuarine lakes and Mississippi Sound. Although the BCS had an undeniable impact on the presence of the coastal cyanoHAB of 2019, other variables including wind direction, water flow, mixing, and persistence of freshwater within the Sound can determine the intensity and extent of the cyanoHABs. Coupling *in situ* phytoplankton information from freshwater water bodies to the marine continuum along with water flow, wind data, and satellite imagery could help identify cyanoHABs at early stages and forecast their trajectory and potential impacts on coastal areas.

Keywords: Bonnet Carré Spillway, cyanobacteria blooms, Harmful Algal Blooms (HABs), Mississippi Sound, river diversions, ocean color

1. Introduction

Harmful algal blooms (HABs) are environmental events that occur when algal populations reach a density threshold which poses negative consequences for environmental and human health (Smayda, 1997). Over the last few decades, the number of reported HABs has risen due to improved conditions for phytoplankton growth, enhanced monitoring, and identifying these events (Bucci et al., 2020; Dai et al., 2023). HABs that are caused by cyanobacteria, photosynthetic prokaryotes, are referred to as cyanoHABs and are found in a wide variety of aquatic environments and conditions worldwide, often associated with eutrophication (Clark et al., 2017).

Although not all cyanobacteria represent a health problem, some are capable of producing toxic secondary metabolites known as cyanotoxins (Ibelings et al., 2021). Despite the caveats to studying the effects of cyanotoxins in humans, laboratory experiments have shown that cyanotoxins are highly neurotoxic and others can damage the liver, kidney, or other organs when ingested, and they can cause skin and/or respiratory irritation (Chorus and Welker, 2021). A common class of cyanotoxins is hepatotoxic microcystins (MCs), with over 100 known variants that can injure or impair the liver function (Vesterkvist et al., 2012). Microcystin poisoning has been documented in pets, livestock, wildlife, and humans through water contact or consumption (Preece et al., 2017 and references therein). CyanoHABs can also cause bothersome odors, hypoxia, and unappealing surface scums creating a potential for detrimental recreational exposure and ecological impact (Codd et al., 2005; Preece et al., 2017; Chorus and Welker, 2021). For these reasons, water quality, fisheries, recreational activities, aquatic life, and public health are all at risk of being negatively affected by cyanoHABs, which thereby pose serious

economic and social consequences (Falconer and Humpage, 2005; Steffensen, 2008; Dodds et al., 2009).

In the Gulf of Mexico, cyanoHABs are commonly found in freshwater and estuarine systems (Downing et al., 2001; Glibert et al., 2005; Boyer, 2008). In Louisiana estuaries, cyanobacteria and the associated toxins have been reported in Lac Des Allemands (Garcia et al., 2010); Breton Sound (Riekenberg et al., 2015); and Lake Pontchartrain (Turner et al., 2002; Bargu et al., 2011; Roy et al., 2013; 2016). The phytoplankton community and the presence of harmful algae, including cyanoHABs, can be influenced by river diversions and the episodic freshwater inflows from the Bonnet Carré Spillway (BCS) (Bargu et al., 2019). Built in 1931, the BCS is a flood control structure that is operated during severe flood events to partially divert water from the Mississippi River into Lake Pontchartrain (Fig. 1). As water accumulates and travels southward down the Mississippi River, the BCS is primarily a fail-safe that has been used 15 times from 1931 to 2022, to protect New Orleans from severe flooding events. Several studies have examined the phytoplankton community during and after BCS openings and found that freshwater diatoms and chlorophytes dominated the system during the Spillway opening, but those were replaced with toxic cyanobacteria species *Microcystis* after the Spillway was closed (Bargu et al., 2011; Roy et al., 2013; 2016).

During the spring and summer of 2019, the coastal communities of Mississippi and Louisiana experienced an unprecedented and detrimental cyanoHAB that forced local agencies to issue water advisories for 25 beaches for almost 3 months along the Mississippi Sound (Fig. 1). The first beach advisory began in mid-June 2019 and by July 7, 2019, a total 25 beaches were under a "water contact warning" that lasted until October 2019 (Mississippi Beach monitoring program data, https://opcgis.deq.state.ms.us/beaches/closures.php, accessed on 01/04/2023). While there

were prior cyanoHABs and other HABs along the Mississippi and Louisiana coast and inside the estuaries that had detrimental effects on the local economies (e.g., Garcia et al., 2010; Riekenberg et al., 2015; Soto et al., 2018), the cyanoHAB occurring in summer of 2019 was the first to force local agencies to take action. In 2019, for the first time in history, the BCS opened twice in one calendar year. The first opening occurred in the winter season for 44 days, from February 27 to April 11. The second opening was from May 10 to July 27 for 79 days, which broke the record for the total number of days the BCS had remained opened.

Previous studies have looked at the Mississippi Sound and Bight (Fig. 1) and how the influx of water from BCS openings can reach the Mississippi Sound and influence the water conditions (Walker et al., 2005; Ren et al., 2009; Gierach et al., 2013; Kemp et al., 2014; Roy et al., 2016; Cambazoglu et al., 2017; Parra et al., 2020; Armstrong et al., 2021). This paper builds upon previous studies and examines the possible link between the BCS openings of 2019, and the extent and duration of cyanoHABs in Lake Pontchartrain, Mississippi Sound, and Bight (Fig. 1). The manuscript is divided into three main objectives. The first is to characterize the spatial and temporal extent of the cyanoHAB that affected the Mississippi coastline in 2019. Many studies have used satellite data to quantify cyanoHABs (Wynne et al., 2008; Clark et al., 2017; Urquhart et al., 2017; Coffer et al., 2020). Here, the National Aeronautics and Space Administration (NASA) ocean color standard Cyanobacteria Index (CI_{cyano}) algorithm was used to detect and examine the spatial and temporal extent of the cyanoHAB. The Cyanobacteria Assessment Network (CyAN), a multi-agency project between the Environmental Protection Agency (EPA), NASA, the National Oceanic and Atmospheric Administration (NOAA), and the United States Geological Survey (USGS), expanded the use of the CI_{cyano} algorithm for monitoring to detect algal blooms in U.S. freshwater systems via remote sensing. In Lake Erie, the CI_{cyano} has proven

to be effective in providing robust estimates of cyanobacteria concentrations where blooms are dominated by *Microcystis* spp. (Wynne et al., 2010). Given that the CI_{cyano} algorithm has primarily been applied in freshwater ecosystems, using it to examine coastal cyanoHABs provides a unique opportunity to also test the capabilities and extend its usability to a wider user community.

The second objective is to couple the CI_{cyano} satellite data with USGS river discharge, salinity, and modeled-wind data from NOAA's High-resolution Rapid Refresh (HRRR) atmospheric model products to study the pre-conditions leading to the cyanoHAB of 2019 and factors aiding the advection and persistence of the bloom within the Mississippi Sound, including the possible relationship to the BCS. The last objective is to further investigate the relationship between cyanoHABs and the BCS by repeating the methods using data from 2018. The year 2018 was selected due to the availability of satellite data, no reports of cyanoHABs along the Mississippi coast, and a BCS opening in March 2018.

2. Methods

2.1 Study area

The study region is composed of several connected bodies of water in the Louisiana-Mississippi region (Fig. 1). From inland outward, as the Mississippi River travels south through the Mississippi Birdfoot Delta, the BCS is adjacent to the Mississippi River. The BCS is approximately 20 miles west and upstream of New Orleans, and opens to Lake Pontchartrain to prevent flooding of the city of New Orleans. Lake Maurepas, northwest of Lake Pontchartrain, feeds into Lake Pontchartrain. The Rigolets is then the primary way that water can travel from

Lake Pontchartrain, out into Lake Borgne, and into the Mississippi Sound. Lake Pontchartrain, when the BCS is not open, is brackish, receiving freshwater from Lake Maurepas, the Tangipahoa, and Tchefuncte Rivers, as well as Bayous Lacombe and Bonfouca, the drainage canals, and saltwater from the Gulf of Mexico.

The Mississippi Sound is the region closest to the shoreline and is separated from the Mississippi Bight by the barrier islands that extend along the coast from Louisiana to Alabama. The Mississippi Sound and Bight are systems dominated by riverine freshwater inputs, primarily by the Mississippi River, then local rivers from Alabama and Mississippi, and the fitful openings of the BCS and other rivers through Lake Pontchartrain and Borgne (Greer et al., 2018; Parra et al., 2020). Other freshwater fluxes include the Tickfaw River that feeds into Lake Maurepas, the Pearl River that feeds into the Rigolets and Lake Borgne, and the Pascagoula, Tchoutacabouffa, Jourdan, and Wolf Rivers that feed into the Mississippi Sound (Cambazoglu et al., 2017; Parra et al., 2020). Overall, the Mississippi Bight is susceptible to intense freshwater inflows during the spring, intermittent tropical storms in the summer, and a drier season in late autumn to early winter (Parra et al., 2020). The hydrographic variability in the Mississippi Sound and Bight is influenced principally by wind and freshwater discharges (Stumpf et al., 1993; Walker et al., 2005), and, to a lesser extent, differential heating and cooling of surface waters (Schiller et al., 2011).

2.2 Remote Sensing: *Ocean color data and CI_{cyano} index*

The CyanoHABs satellite remote sensing analysis used NASA's ocean color standard CyAN product, CI_{cyano}. The data were gathered by the European Space Agency (ESA) using two Ocean and Land Color Instruments (OLCI) sensors onboard Sentinel-3A (2016-present) and Sentinel-3B (2018-present). OLCI has a temporal resolution of every 2-3 days and a spatial

resolution of ~300m; however, combined data from Sentinel-3A and 3B provide superior coverage. For example, between June 9 and July 6, 2019 (27 days), the percentage of days with usable data increased from 40.7% with only Sentinel-3A to 77.8% of days when combined with Sentinel-3B.

CI_{cyano} uses Rayleigh-corrected top-of-atmosphere reflectance and is a derivative spectral shape algorithm,centered at 681 nm (Wynne et al., 2008; Seegers et al., 2021). The curvature of the spectral shape in the targeted spectral range is sensitive to chlorophyll-a (chl-a) and phycocyanin absorption, less sensitive to atmospheric effects, and therefore can be used to assess cyanobacteria populations. CI_{cyano} relies on Rayleigh-corrected top-of-atmosphere reflectance measurements near the red-edge of the visible spectrum and a spectral shape algorithm approach because they tend to be less sensitive to atmospheric correction compared to other spectral ranges and algorithm types. The CyAN CI_{cyano} product is produced and distributed for the contiguous United States and Alaska by the NASA Ocean Biology Processing Group (OBPG; https://oceancolor.gsfc.nasa.gov) at NASA Goddard Space Flight Center. For this study, daily and weekly maximum GeoTIFF composites of CI_{cyano} from February 1 to September 20 of 2018 and 2019 were downloaded from https://oceandata.sci.gsfc.nasa.gov/api/cyan_file_search (doi: 10.5067/SENTINEL-3A/OLCI/L3M/CYAN/CI/4 and doi: 10.5067/MERGED-S3/OLCI/L3M/CYAN/CI/4). The GeoTIFF data is provided as digital numbers (DN), where 0 indicates data below the threshold of CI_{cyano} detection limits, 1-253 indicates valid data, 254 indicates land, and 255 indicates that no data are available for selected pixels. CI_{cyano} is calculated from valid DN values following: CI_{cyano}=10^(3.0/250.0*DN−4.2). Weekly maximum composites of CI_{cyano} were used for visual analysis and determination of the

location and extension of CyanoHABs. NASA's SeaDAS (version 7.3.2) ocean-color display and analysis software suite (http://seadas.gsfc.nasa.gov/) was used to convert from DN to CI_{cyano} and to visualize the resulting images. The region of interest was cropped, color schemes were re-designed, and images (PNGs) were created. Daily images were additionally used to determine the frequency and intensity of cyanobacteria in the region of interest and to create monthly frequency maps using Python 3.7. The Python code read the daily images using the Rasterio module, converted the data from DN to CI_{cyano}, and calculated the frequency per pixel of CI_{cyano} equal to or above 0.001, which corresponds to 6 µg L-1 and a low concentration of cyanobacteria (Lunetta et al., 2015; Tomlinson et al., 2016). The frequency data were normalized per number of valid data per pixel and per month. The World Health Organization thresholds for recreational exposure to cyanoHABs are reported in chl-a units for waters dominated by cyanobacteria with the Vigilance Level range being 1-12 and Alert Level 1 range being 12-24 µg L^{-1} (Chorus and Welker, 2021). CI_{cyano} can estimate chl-a values using the equation from Seegers et al. (2021):

$$\text{chl-a} = CIcyano * 6620$$

where the intercept is assumed to be zero. For the frequency analysis, the threshold to categorize a pixel as "cyanoHAB" was when the CI_{cyano} was 0.001 (~6 µg chl-a L^{-1}), which is the minimum detection limit for the CI_{cyano} algorithm (Lunetta et al., 2015). In the analysis of the weekly images, we refer to a "bloom" when the area with a CI_{cyano} above 0.001 exceeds several square kilometers (>20 pixels, where one pixel is ~0.09 km^2).

2.3 Ancillary data: ***salinity, wind, river discharge, and beach advisories***

Historical river discharge data from the Tickfaw (USGS 07376000 Tickfaw River at Holden, LA; 30°30'13"N, 90°40'38"W), Tangipahoa (USGS 07375500 Tangipahoa River at Robert, LA; 30°30'23"N, 90°21'42"W), and Pearl rivers (Station USGS 02489500 Pearl River near Bogalusa,

LA; 30°47'35"N, 89°49'15"W) were downloaded from USGS's National Water Information System (https://waterdata.usgs.gov/nwis).

Information on beach advisories was obtained from the Mississippi Beach Monitoring Program. There are 21 stations spread out along Mississippi's coast from Lakeshore Beach to Pascagoula Beach (https://opcgis.deq.state.ms.us/beaches/closures.php).

Salinity data were obtained from the Mississippi Department of Marine Resources (MDMR) real-time hydrological monitoring stations that operate in partnership with the U.S. Geological Survey (USGS) in the Mississippi Sound. The stations are maintained to USGS specification (Wagner et al., 2006) with calibration uncertainties not exceeding ±5 mS cm^{-1} (roughly salinity of 0.01). The instruments are mounted near the sea-floor and measure temperature, salinity, and pressure (https://dmr.ms.gov/hydrological-monitoring/). Only data for MDMR/USGS station 10 (301104089253400 Mississippi Sound at USGS St. Joseph Island Light, MS; 30°11'27"N, 89°25'20"W) and station 6 (301527088521500 Mississippi Sound at USGS East Ship Island, MS; 30°15'16"N, 88°52'08"W) are used in this study. While salinity measurements were not available for both stations, conductance at 25°C was converted to salinity using the guidelines by Wagner et al. (2006).

Wind data were obtained from NOAA's High-Resolution Rapid Refresh (HRRR) atmospheric model products. HRRR is a real-time 3-km resolution atmospheric model with hourly output frequency (https://rapidrefresh.noaa.gov/hrrr/) and assimilates radar data every 15 minutes over a 1-hour period. The high spatial and temporal resolution of HRRR allows the model to capture land-sea breeze, which has a strong impact on the circulation and water exchange in the shallow estuaries of the study area (Armstrong et al., 2021; Bouchard, 2021, Saran et al., 2022).

3. Results

At the beginning of 2019, flooding occurred in the Midwest during the winter and spring months. The contiguous U.S. average annual precipitation in 2019 was 883 mm (34.78 in), which is 123 mm (4.84 in) above the long-term average. The year 2019 is currently the second wettest year on record and only 4.5 mm (0.18 in) less precipitation than the total for the wettest year set in 1973 (NOAA NCEI, 2020). Most notably, in 2019 there was flooding along the Missouri River and its tributaries throughout Nebraska and Iowa (USGS), which both fall within the Mississippi River watershed. The accumulation of flooding within the Mississippi River broke the record for the number of consecutive days the water height exceeded the 4.6 m level in New Orleans (Gasparini and Yuill, 2020). Totaling 164 days, from October 1, 2018, to September 30, 2019, the Mississippi River water height of 2018-2019 exceeded the previous record holder of 49 days set during 1990-1991 (See Fig. 1 in Gasparini and Yuill, 2020).

The heavy rains and flooding along the Mississippi and Ohio River Valley led to unprecedented high river discharge along the Mississippi River and its tributaries, as well as other river basins in our study area (e.g., the Pearl River Basin). Fig. 2 shows the daily median river discharge from 2018 and 2019 for the Tickfaw River (A) that feeds into Lake Maurepas; the Tangipahoa River (B) that feeds into Lake Pontchartrain; and the Pearl River (C) that feeds into the Rigolets and Lake Borgne and is part of the Pearl River Basin. From January to early April of 2018, river discharge was higher than the 25-year climatological mean (full gray line in Fig. 2), which led to the 2018 BCS opening from March 8 to March 30, 2018. Hereafter, river discharge was within the mean for the rest of the year until late October, when there was a large peak in river discharge up to 500 m^3s^{-1} at the Pearl River and an even larger peak (>1000 m^3s^{-1}) in late December. High

river discharge continued into early 2019 for all rivers. For the Tickfaw and Tangipahoa Rivers, river discharge returned to mean levels between February and April 2019; however, high river stages persisted and discharge in the Pearl River remained above the climatological mean. Continuous heavy precipitation led to the first 2019 BCS opening from February 27 to April 11, 2019 (44 days). River discharge rose (above the climatological mean) again in mid-April and May for all rivers, leading to the second BCS opening that year from May 10 to July 27, 2019 (79 days).

Variability in salinity was evaluated at two MDMR/USGS stations, selected to represent coastal towns of the western Mississippi Sound (Station 10 near Bay St. Louis, Fig. 3 black line), and an area further from the BCS discharge zone and closer to the Mississippi Shelf (Station 6 near Ship Island Passage, Fig. 3 blue line). In 2018, salinity at Station 10 was low (< 10), reaching values below 5 during several periods between March and May (Fig. 3a). After July of 2018, salinity at Station 10 increased above 10. At Station 6, salinity was above 20 for most of 2018 with visible fluctuations (Fig. 3a). In 2019, salinity at Station 10 was near 0 from March to mid-July, with a noticeable increase on July 15 (Fig. 3b), coinciding with the landfall of Hurricane Barry at southwest Louisiana on July 13 (Cangiolasi et al., 2019). After the hurricane, salinity dropped to near 0 until the first week of August and subsequently increased to 10-15 for the rest of the year. A decrease in salinity was observed at Station 6, with April values of 20 decreasing to near 0 by late May and increasing slowly above 20 by mid-June 2019. Unfortunately, data was not available for the summer until August, and after that, salinities remained greater than 20 (Fig. 3b).

In late June 2019, the Mississippi Department of Environmental Quality issued a “water-contact advisory” for 25 beaches along the Mississippi coast (21 sand beach segments, as well as the

four non-standard segments that are not included in their 21 monitoring stations). Fig. 4 shows the start date, duration, and timing of water advisories for the 21 Mississippi Beach Monitoring Program stations from Lakeshore Beach (westernmost station) to Pascagoula Beach (easternmost station), displaying a predominant west-to-east progression pattern in advisories. Although most news reports referred to beach closures, the beaches were closed only from late June 2019 to July 10, 2019 (Fig. 4); after, beaches were only under a "water contact warning", which advised people and their pets to avoid contact with the water, including swimming. Advisories for all beaches were lifted on October 5, 2019.

To get a better picture of the spatial and temporal extent of the cyanobacteria bloom, CI_{cyano} satellite ocean color imagery from February to September 2018 and 2019 were analyzed. As an exploratory analysis, CI_{cyano} monthly frequency maps were derived, and summarized results are depicted in Fig. 5 and Fig. 6. While we found no official local reports of cyanobacteria bloom in 2018 along the Mississippi Sound, our results suggest that there was a cyanobacteria bloom in Lake Pontchartrain from February to May 2018, with the highest frequency (present in over 60% available pixels) during the month of March (Fig. 5, yellow region). However, there were no signs of the bloom exiting the lake or blooms near the Mississippi Sound region. After May, there were no blooms observed in the imagery, and therefore a single frequency map for June to September was provided for 2018.

The CI_{cyano} monthly frequency maps for 2019 depict a different timeline than for 2018 (Fig. 6). From February to the end of April 2019, there was little to no bloom occurrence. The initial bloom was observed in May near Bay Boudreau and Drum Bay, LA (Northwest of the Chandeleur Sound) and all the way to Biloxi and Ocean Springs, MS. June was a very active bloom month with a higher frequency of elevated CI_{cyano} pixels mainly in Lake Borgne and Lake

Pontchartrain near the Tchefuncte River discharge area (>50%), with the bloom area extended all the way to Bay St. Louis, MS. The higher frequency of bloom-level CI_{cyano} pixels in Lake Borgne (35% of available pixels) continued into July and decreased towards September, while the bloom in Lake Pontchartrain continued all the way to September (~40%) near the Tchefuncte river discharge area.

The 2019 CI_{cyano} weekly images were examined for a detailed view of bloom extension and possible bloom dispersal. Weekly images from April 21 to August 3 are shown in Fig. 7, with additional 2019 weekly images included in Appendix A and Appendix B. Several low CI_{cyano} index (<0.001) pixels can be observed in the week of April 21-27, 2019 near Lake Borgne, Bay Boudreau, and Drum Bay (Fig. 7). Yet, by the week of April 28 - May 4, the bloom region became a large area (> 20 pixels) with $CI_{cyano} > 0.001$ (> ~6 ug chl-a L^{-1}) covering all of Bay Boudreau and extending all the way to Oyster Bay in the direction of Cat Island, MS. The bloom intensified and advected north-eastward towards Biloxi and reached the eastern side of the Mississippi Sound by the week of May 12-18, 2019. The cyanoHAB seemed to dissipate by June 1, 2019; however, remnants remained throughout the Mississippi Sound and Mississippi Shelf. A parallel and most likely unrelated bloom (5 to 10 km^2 with pixels $CI_{cyano}>0.001$) can be observed in Lake Pontchartrain the week of May 26 - June 1, 2019, near Lake Maurepas and the discharge area of the Tchefuncte River. This secondary bloom intensified by the following week and a filament advected from the Tchefuncte River discharge area towards Lake Borgne is visible the week of June 2-8, 2019, with $CI_{cyano}>0.001$. The bloom intensified, with visible increases in CI_{cyano} up to 0.07 (>400 ug chl-a L^{-1}), extending from Lake Pontchartrain (all Southeast region) to Lake Borgne and reaching Bay St. Louis with the Mississippi Sound by June 9-15, 2019. The most intense part of the bloom seemed to remain inside Lake Borgne, although bloom pixels

were observed all along the Mississippi Coast until July 6, 2019. The bloom lost intensity between July 7-20, 2019, with decreasing concentrations coinciding with the landfall of Hurricane Barry on July 15, 2019. The bloom re-intensified the last week of July and continued to the end of September (see Fig. 7 and Appendix B), with higher intensity inside Lake Pontchartrain; note, the bloom remained present along the Mississippi Sound and Lake Borgne in lower concentrations.

Modeled wind data was used to better understand regional water circulation and the patterns observed in the ocean color imagery. Multiple locations were used during the analysis, however only results for station W2 (30°13'12"N, 90°7'48"W, Lake Pontchartrain near the rigolets) and W6 (30°19'48"N, 89°19'12"W, Bay St. Louis) are presented here. Wind roses plots provided an overall view of the intensity and direction of the winds at those two stations from March through July 2019 (Fig. 8). At station W2, winds were predominantly southeasterly (~90-170°) from March to July with winds speeds <9 ms^{-1} most of the time. A large percentage of the winds were southerly around 170 degrees and sometimes winds exceeded 9 ms^{-1}. Station W6, near Bay St. Louis, shows similar patterns to Station W2, but with less variable southerly winds (~150-170°) dominating over 50% of the time between March to July 2019.

To better understand the shifts in wind direction and speed observed from May to July, the modeled wind speed and direction time series for both stations were compared (Fig. 9). The first wind direction shift (from southeasterlies to southwesterlies) is seen from ~May 12-17, 2019, at both stations. At station W6, southerly and southeasterly winds remained dominant for the rest of May. A second wind shift event is observed during the first two weeks of June and then again at the end of June and the beginning of July. Wind direction variability increased considerably at the end of July and into August with predominant northwesterlies. Wind speeds were mainly

below 10 ms^{-1}, except during the landfall of Hurricane Barry. Station W2 shows very similar wind patterns, with a main wind shift event from May 12-17 and a shorter event from May 25-29, 2019. Wind direction was highly variable for the first half of June, with northwesterlies winds from June 9-14, 2019. Southwesterlies winds continued during the second half of June, and another drastic shift was observed in the first ~10 days of July with Northwesterlies winds. The effects of Hurricane Barry were also seen from July 12-17 with higher winds speeds reaching 15 ms^{-1}.

4. Discussion

Blooms with high levels of toxic cyanobacteria have been documented in Lake Pontchartrain following previous BCS openings (Turner et al., 2002; Bargu et al., 2011; Roy et al., 2013), as well as other nearby lakes and estuaries, such as Breton Sound (Riekenberg et al., 2015) and Lac des Allemands (Garcia et al., 2010). More specifically, the toxic cyanobacteria species *Mycrocystis* have been observed to slowly replace freshwater diatoms and chlorophytes after the Spillway was closed (Bargu et al., 2011; Roy et al., 2013; 2016). In this study, cyanobacteria blooms were observed in Lake Pontchartrain 10 to 15 days after the opening of the BCS in March of 2018 and the second opening of the BCS in the summer of 2019, but not following the first 2019 BCS opening of February-April 2019. Of the two blooms observed inside Lake Pontchartrain post-BCS opening, only the bloom of summer 2019 exited the lake and reached the coastal waters of Mississippi. In March 2019, a separate cyanoHAB was also observed in the Breton Sound region, Bay Boudreau, and Drum Bay and reached the Mississippi coastal waters, six weeks before the beaches in Mississippi were closed. Both blooms were advected into the

Mississippi Sound and likely contributed to the 3-month-long beach water advisories of 2019 along the Mississippi coastline.

4.1. Wind- and Buoyancy-driven flows and cyanoHAB scenarios

Although there could be numerous factors (e.g., nutrients, water temperature, and water mixing or stagnation) that could determine the fate of cyanoHABs, in the study region, wind- and buoyancy- driven flows play a crucial role in the advection and dispersion of any type of HABs as well as other events, such as oil spills. In the Mississippi Bight, wind forcing and freshwater discharge are the main drivers of the flow structure on the shelf, the mixing, and the transport of plume and nonplume surface waters on the shelf. Circulation within this system is regulated by stratification that promotes wind-driven coastal Ekman transport (Dzwonkowski et al., 2011). These physical interactions are important for generating wind- and buoyancy-driven flows that ultimately influence the structure of regional food webs (Parra et al., 2020). Seasonal winds present two main patterns with relatively strong southward winds from passing cold fronts primarily in winter and spring, while summer and fall are relatively calm with weaker northward winds. The frequent fall and winter cold fronts (every 3–10 days) generate relatively strong southward winds (>10 ms^{-1}) that push the Mississippi River plume toward the west and south and mix shelf waters. On the other hand, spring and summer consist of weaker (<5 ms^{-1}) northward winds that transport the Mississippi River plume eastward into the Mississippi Bight (Morey et al., 2003a; 2003b; Schiller et al., 2011; Dzwonkowski et al., 2018). With this wind seasonality and subsequent Mississippi River transport, waters moving through the BCS would take starkly different paths depending on the time of year.

Parra et al. (2020) showed that BCS waters from the winter 2016 BCS opening remained within the estuarine lakes and sounds; this suggests that if the BCS opening had happened during the

spring and summer when mild northward winds predominate, BCS waters would most likely travel eastward into the Mississippi Bight. From March 2019 to the end of July 2019, winds were predominantly northwestward; therefore, waters were mostly prevented from flushing out into the Mississippi Shelf and instead were retained in the estuary system (in this case, Lake Borgne and the Mississippi Sound). Concurrently, BCS flood waters would create a buoyancy-driven flow out of Lake Pontchartrain into Lake Borgne and subsequently the Mississippi Sound. The synergy of wind- and buoyancy-driven flows converted the Mississippi Sound estuary into a "semi-enclosed lake" for several months; thus, with the summer increase in temperatures, the entire region became a more ideal environment for cyanoHABs. Slight shifts in wind directions (northward and northeastward) during the month of June allowed waters to slightly flow eastward but not out of the Mississippi Sound. While that synergy was broken temporarily during Hurricane Barry (mid-July), the cyanoHAB re-emerged and lingered until the end of August, when stronger episodic wind-shift events increased mixing and seawater exchange between the Mississippi Sound and Shelf.

During the 2018 BCS opening, the results showed a similar scenario to the one observed by Parra et al. (2020) for the 2016 winter BCS opening. A relatively short (22 days) BCS opening in the late winter - early spring with predominantly Southeasterlies limited the flow out of Lake Pontchartrain, and possibly prevented the advection of the bloom towards Lake Borgne and the Mississippi Sound. If the 2018 BCS remained open for a few more weeks into the spring, the scenario could have been completely different. The combination of stronger northward winds with intense buoyancy flow due to extended freshwater inflow can facilitate bloom advection into the Mississippi Sound. Nonetheless, cyanoHAB retention and their ability to thrive within the Mississippi Sound will also depend on the nutrient availability, temperature, salinity, mixing, and

very important wind-shift events, which will ultimately determine the seawater exchange between the estuary and the shelf.

4.2. River diversions

The expansion of cyanoHABs across the aquatic continuum in a variety of systems has been extensively discussed by Paerl et al. (2018) and Zepernick et al. (2022), including events in the northern Gulf of Mexico (Bargu et al., 2019), coastal Pacific water California and Oregon (Ger et al., 2009; Miller et al., 2010; Genzoli and Kann, 2020), and the controversial *Microcystis* blooms in Lake Okeechobee that were transported downstream into the Indian River Lagoon, Sanibel Estuary, and coastal waters of the Florida coastlines (Rosen et al., 2018; Metcalf et al., 2021). The 2019 cyanoHAB along the Mississippi coast is a similar scenario to that seen in Lake Okeechobee with freshwater releases leading to coastal blooms.

Freshwater diversions in the Lower Mississippi River play an important role in the outflow of freshwater, sediment, and nutrients, and drive phytoplankton dynamics in the region, as well as adjacent estuarine systems such as the Mississippi Sound, and into the northern Gulf of Mexico. Future restoration plans for the Mississippi River Delta include the construction of additional large-scale sediment diversions into the Barataria and Breton Sound estuaries (Coastal Protection and Restoration Authority of Louisiana, 2017). The fact that there were no cyanoHABs in Lake Pontchartrain until late May of 2019, but a cyanoHAB was in the Breton Sound as early as March, suggests that management of water outflow and phytoplankton monitoring in this region should not be limited to the large river diversions like the BCS and Lake Pontchartrain, respectively. Other diversions, such as Caernarvon and Davis Pond freshwater diversions, contribute to the outflow of freshwater and nutrients, and possibly the transport of toxin-producing freshwater cyanobacteria into brackish coastal environments. This, as well as the

potential future restoration plans for the region, highlights the need for improved, multi-state, multidisciplinary, and continuous monitoring programs that integrate biogeochemical sampling (e.g., phytoplankton, pigments, nutrients), hydrographic measurements (e.g., temperature, salinity, oxygen), satellite imagery, and circulation models.

4.3. Monitoring and forecasting tools and limitations

Ocean color imagery allowed a view back in time to better characterize the spatial and temporal extension of the bloom, which could not be done with traditional water sampling. The CI_{cyano} images were successfully used to characterize the spatial and temporal extent of the 2019 cyanoHAB that impacted the Mississippi coast. To the best of our knowledge, this is the first time the CI_{cyano} was used to characterize blooms in near-coastal waters, demonstrating the potential for monitoring purposes from inland waters (i.e., Lake Pontchartrain) to coastal waters (i.e., Mississippi Sound). Similar to all ocean color products, the use of the CI_{cyano} has several limitations and caveats, such as cloud cover, atmospheric correction, and the need for validation. One other caveat when using CIcyano is that it is only showing the surface expression of the bloom. Wind-induced mixing could have mixed some of the bloom into the water column, therefore underestimating bloom concentration and extent. The CI_{cyano} does not provide information about toxicity or specific information about the species causing the bloom; therefore, it relies on field monitoring for validation. It does allow for a strategic selection of field sites and a larger spatial view of the affected area when confirmed. Coupling the CI_{cyano} imagery with model-wind data provided a better understanding of how the bloom reached as far as the Mississippi Sound and why it persisted for an extended time. Results presented here set the stages for further research as to how the use of ocean color imagery, ancillary data (i.e., wind, salinity, water temperature), and high-resolution circulation models can be used for monitoring

and forecasting of cyanoHABs in this region. Wind data provides a general understanding of the atmospherically driven circulation patterns in this shallow water estuarine system, however, for forecast studies, high resolution ocean models such as a Regional Ocean Modeling System (ROMS) application within the Coupled Ocean Atmosphere Wave Sediment Transport (COAWST) modeling system framework could be used (Parra et al., 2020; Armstrong et al., 2021; Saran et al., 2022).

4.4. Implications for public health and coastal communities

As global warming and climate changes continue, every region in the world will face further increases in climate hazards, increasing multiple risks to ecosystems and humans (e.g., flooding in coastal and other low-lying cities) and those risks will become increasingly complex and more difficult to manage (IPCC, 2023). CyanoHABs are a common hazard for inland water bodies (Chorus and Welker, 2021), but the expansion of cyanoHABs across the aquatic continuum represents a forthcoming risk for coastal communities. Once beaches popular with tourists become slimy and green and the warning signs scare beachgoers away, the economy of these coastal towns will be jeopardized. The economic effects cascade when toxins are detected and shellfish beds are closed for prolonged times.

The unprecedented precipitation and flooding along the Mississippi watershed that forced the BCS to open twice in one year for 122 days total and the subsequent cyanoHAB along the Mississippi coast are undoubtedly examples of the hazards and complexities humans may confront in the upcoming decades (IPCC, 2023). In the case of the 2019 cyanoHAB, the cyanoHABs were not only going from freshwater environment to marine environment, but also from Louisiana to Mississippi waters. Therefore, if the expansion of cyanoHABs continues its

trend, the coordination for monitoring programs, management of river diversion, and decision-making among states will become critical.

5. Conclusions

Understanding climate change and the worldwide trends of HABs is undeniably a global concern. The UNESCO's Intergovernmental Oceanographic Commission released a comprehensive worldwide data analysis and found that the perceived global increase in algal blooms is attributable to intensified monitoring and emerging bloom impacts (Hallegraef et al., 2021). A recent study by Dai et al. (2023) used ocean color to confirm global increasing trends in spatial extent and frequency of coastal algal blooms that can be traced back to human-driven perturbations of global or local systems. Emerging technology methods like satellite ocean color and the development and refinement of satellite-derived algorithms for the detection of HABs such as CI_{cyano} have revolutionized how phytoplankton are monitored. The way we study phytoplankton and HABs from space is expected to evolve even more in the near future, as NASA develops new ocean color missions including the Plankton, Aerosol, Cloud, ocean Ecosystem (PACE), which will provide daily global, 1-km resolution hyperspectral observations of the open ocean and coastal and inland waters; the Geostationary Littoral Imaging and Monitoring Radiometer (GLIMR), which will provide 300-m observations of U.S. regional coastal and inland waters several times a day; and the Surface Biology and Geology (SBG), which aims to collect global observations at 30-m resolution of coastal and inland waters over several days.

While Hallegraef et al. (2021) found no conclusive trend on the global increase in HAB frequency, they agree that, as the human population continues to increase alongside climate

change and human pressure on our ecosystem (similar to findings of Dai et al., 2023), HABs will increasingly constitute a serious threat to public health, recreational activities, tourism, and fisheries, and therefore present a problem for the economy. Since 2015, coastal towns along the Mississippi Sound experienced several intense *Karenia brevis* blooms (Soto et al., 2018; Jackson et al., 2022), as well as the cyanobacteria bloom in 2019 responsible for the 3-month-long beach advisories. Although the dynamics of these blooms were very different, both cases show the connectivity that crossed state boundaries. In the case of *Karenia brevis* blooms, there was advection from the Florida Panhandle towards the Mississippi Sound; cyanobacteria blooms were transported from inland water bodies such as Lake Pontchartrain, Louisiana, towards the coastal waters of the Mississippi Sound. There was also the undeniable impact of the BCS opening on the presence of the coastal cyanoHAB of 2019. The relationship between BCS openings and the presence of cyanoHABs within the Mississippi Sound is very complex and will depend on many factors (e.g., length of the BCS opening, freshwater discharge, wind direction, water flow, mixing, and nutrient loading). For 2019, the synergy of wind- and buoyancy-driven flows converted the Mississippi Sound estuary into a "semi-enclosed lake" for several months; with salinities near zero for several months, the BCS opened for more than 100 days, and the warm summer temperatures, the entire region became an ideal environment for cyanoHABs. Undoubtedly there exists a need for a better understanding of the phytoplankton dynamics across the aquatic continuum and an improvement of monitoring programs with the integration of satellite imagery and circulation models (Dai et al., 2023). The resulting information could be used when managing the river diversions and spillway openings; e.g., if feasible, timing them during the periods when the probability of cyanoHABs is low. Finally, as Jackson et al. (2022) stated, there is a need to encourage coordination and collaboration among federal and state

agencies, academic units, non-governmental organizations, and other stakeholders for HAB monitoring programs across all the states in this region.

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7. Figure captions

Figure 1. Map of the study region. Rivers are shown in blue lines. Salinity stations (S10 and S6) shown in blue squares. USGS River stations (Tickfaw, Tangipahoa and Pearl Rivers) shown in purple diamonds. The locations of those three rivers are also shown; note that the stations are

usually upstream. The Mississippi Beach Monitoring Stations are shown in green, and their id's go from 1 to 20 from West to East. The locations where the modeled wind data were extracted are shown using red circles and labeled as W2 (Lake Pontchartrain station) and W6 (Bay St. Louis station).

Figure 2. River discharge data from three rivers. The Tickfaw River (A) feeds into Lake Maurepas. The Tangipahoa (B) River feeds into Lake Pontchartrain. The Pearl River (C) feeds into the Rigolets. Three discharge peaks were omitted on subplot B for comparison purposes: peak on May 13, 2019, with 280.5 $m^3 s^{-1}$, peak on October 27, 2019 with 300 with 298.7 $m^3 s^{-1}$, peak on December 29, 2019 with 533.8 $m^3 s^{-1.}$

Figure 3. Salinity data from February 2018 (Panel A) and 2019 (Panel B) for Station 6 near Ship Island Passage (blue line) and Station 10 near Bay St. Louis (black line).

Figure 4. The duration and timing of water advisories for the 21 Mississippi Beach Monitoring Program stations from Lakeshore Beach (Station 1) to Pascagoula Beach (Station 20), Mississippi for the summer of 2019.

Figure 5. Percent frequency per pixel of CI_{cyano} equal to or above 0.001 normalized per number of valid data per pixel and per time frame in 2018.

Figure 6. Percent frequency per pixel of CI_{cyano} equal to or above 0.001 normalized per number of valid data per pixel and per time frame in 2019.

Figure 7. Weekly CI_{cyano} composites from April to August 2019.

Figure 8. Wind roses from March 1 to July 31, 2019, for Site 2 in Lake Pontchartrain near the Rigolets, LA and Site 6 in Bay St. Louis, MS. Wind direction is in degrees and wind speed in m s^{-1}.

Figure 9. Modeled wind magnitude (ms^{-1}) and direction (°) time series extracted at station 2 (Lake Pontchartrain, LA) and Station 6 (Bay St. Louis, MS).

Appendix A. Weekly CI_{cyano} composites from March 10 to April 20, 2019.

Appendix B. Weekly CI_{cyano} composites from August 11 to September 21, 2019.

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Figure 1

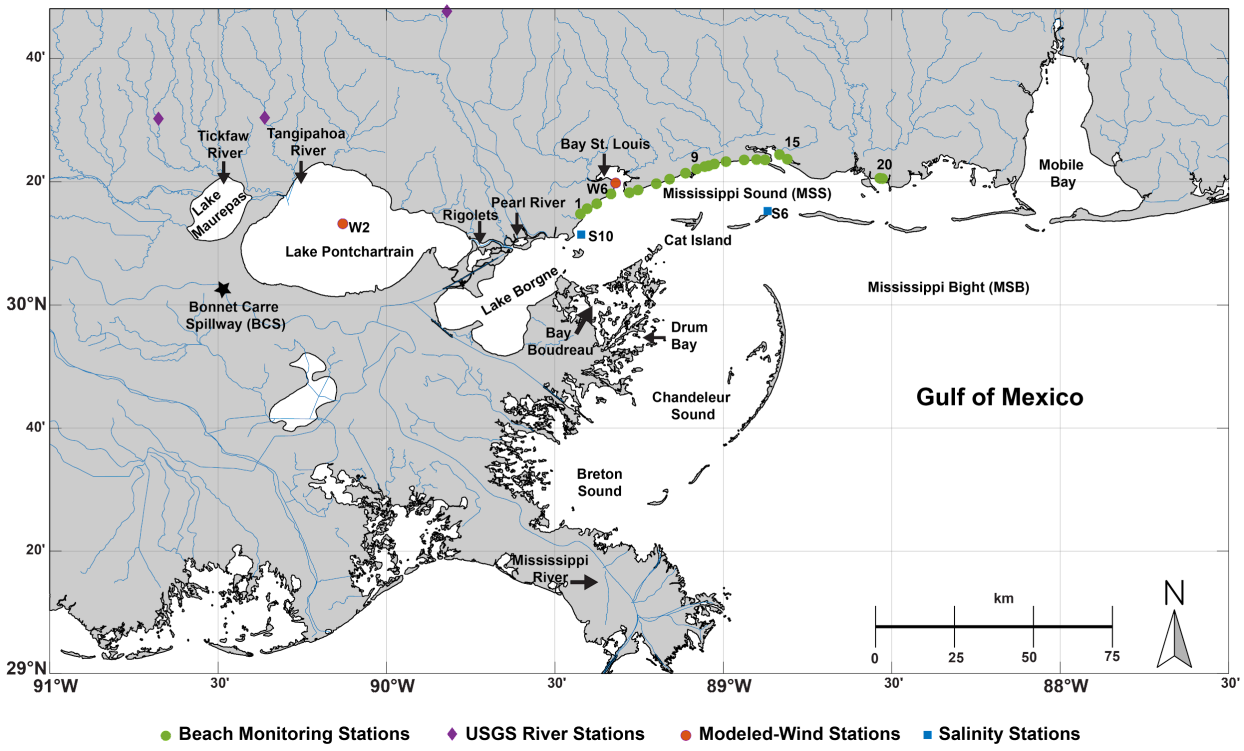

Tickfaw River
Tangipahoa River
Lake Maurepas
W2
Lake Pontchartrain
Bonnet Carre Spillway (BCS)
Rigolets
Pearl River
Bay St. Louis
W6
1
9
15
20
Mobile Bay
Mississippi Sound (MSS)
S6
S10
Cat Island
Lake Borgne
Bay Boudreau
Drum Bay
Mississippi Bight (MSB)
Gulf of Mexico
Chandeleur Sound
Breton Sound
Mississippi River
km
0
25
50
75
N
40'
20'
30°N
40'
20'
29°N
91°W
30'
90°W
30'
89°W
30'
88°W
30'
Beach Monitoring Stations
USGS River Stations
Modeled-Wind Stations
Salinity Stations

Figure 2

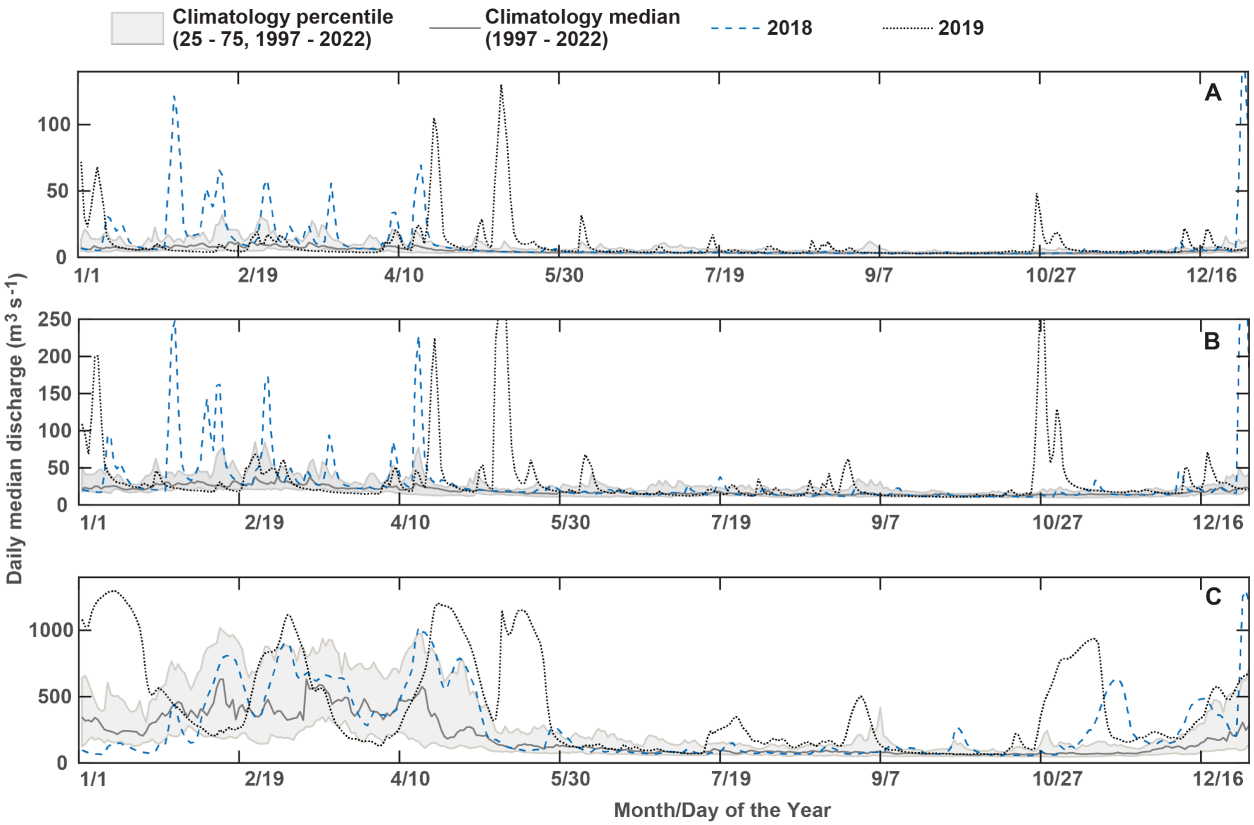

Climatology percentile
(25 - 75, 1997 - 2022)
Climatology median
(1997 - 2022)
2018
2019
A
B
C
Daily median discharge (m3 s-1)
Month/Day of the Year
1/1
2/19
4/10
5/30
7/19
9/7
10/27
12/16

Figure 3

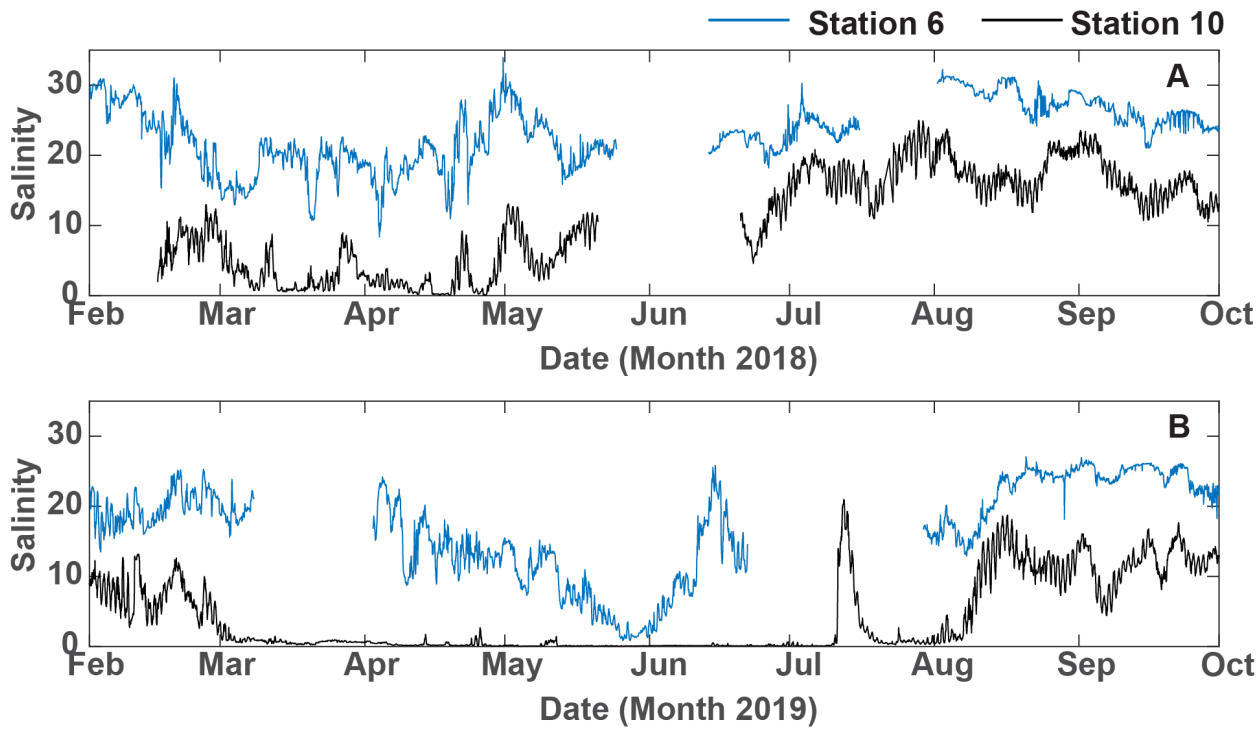


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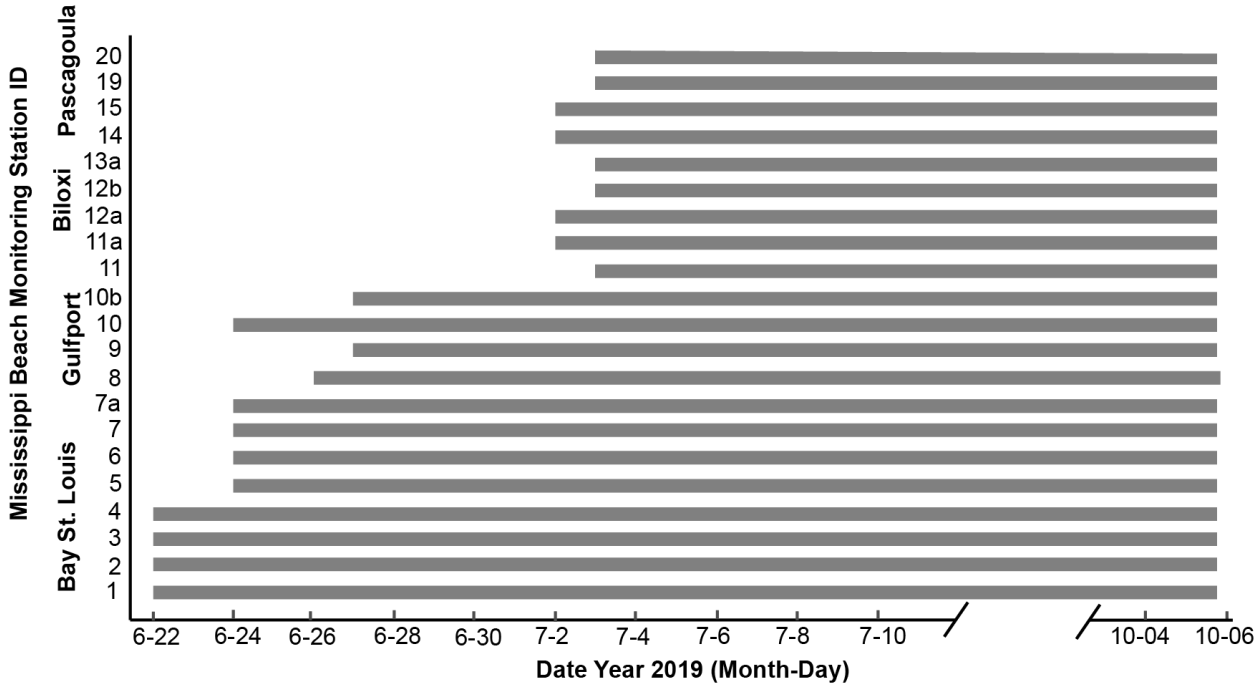


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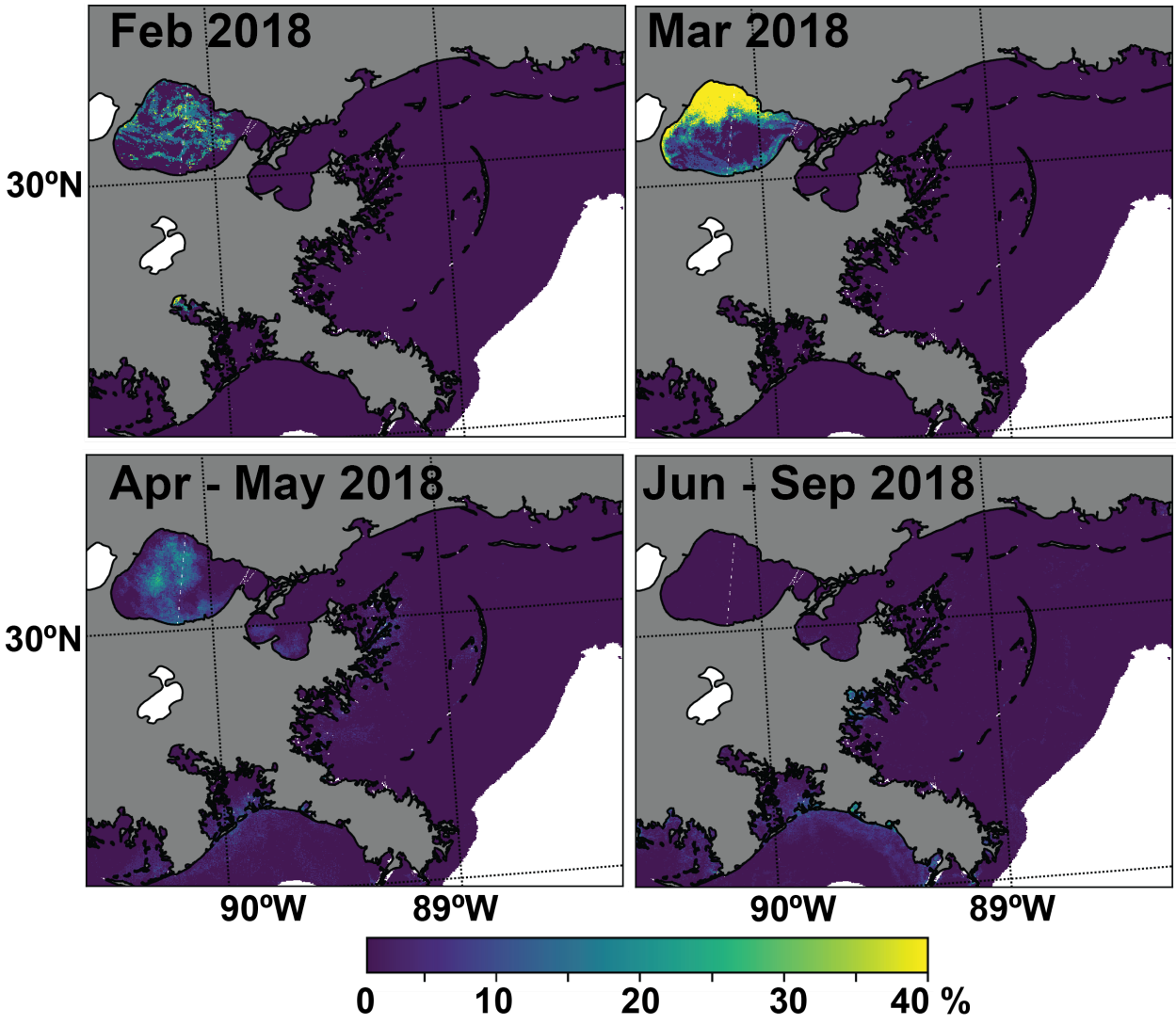

Feb 2018
Mar 2018
Apr - May 2018
Jun - Sep 2018
30°N
30°N
90°W
89°W
90°W
89°W
0
10
20
30
40 %

Figure 6

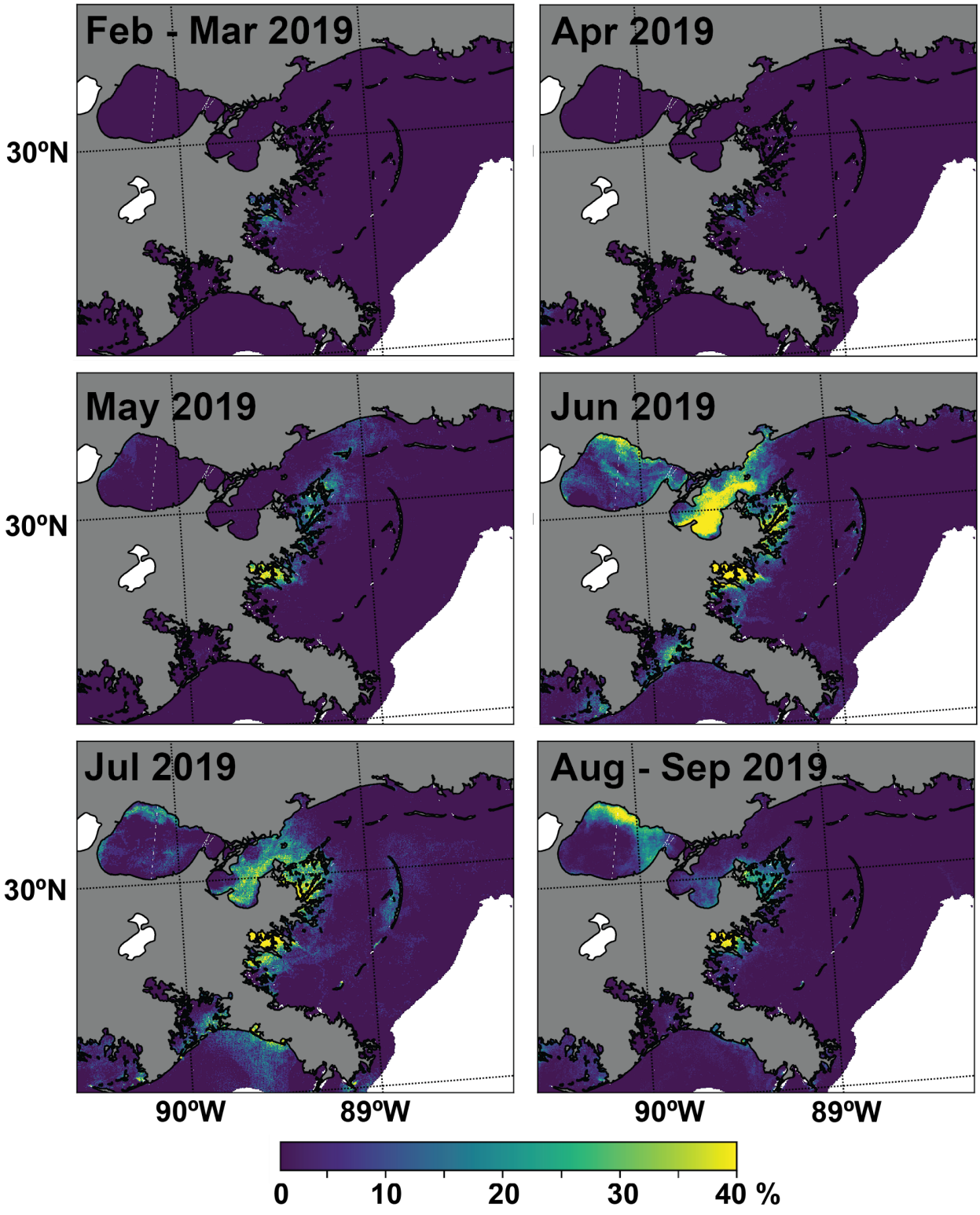

Feb - Mar 2019
Apr 2019
May 2019
Jun 2019
Jul 2019
Aug - Sep 2019
30ºN
30ºN
30ºN
90ºW
89ºW
90ºW
89ºW
0
10
20
30
40 %

Figure 7

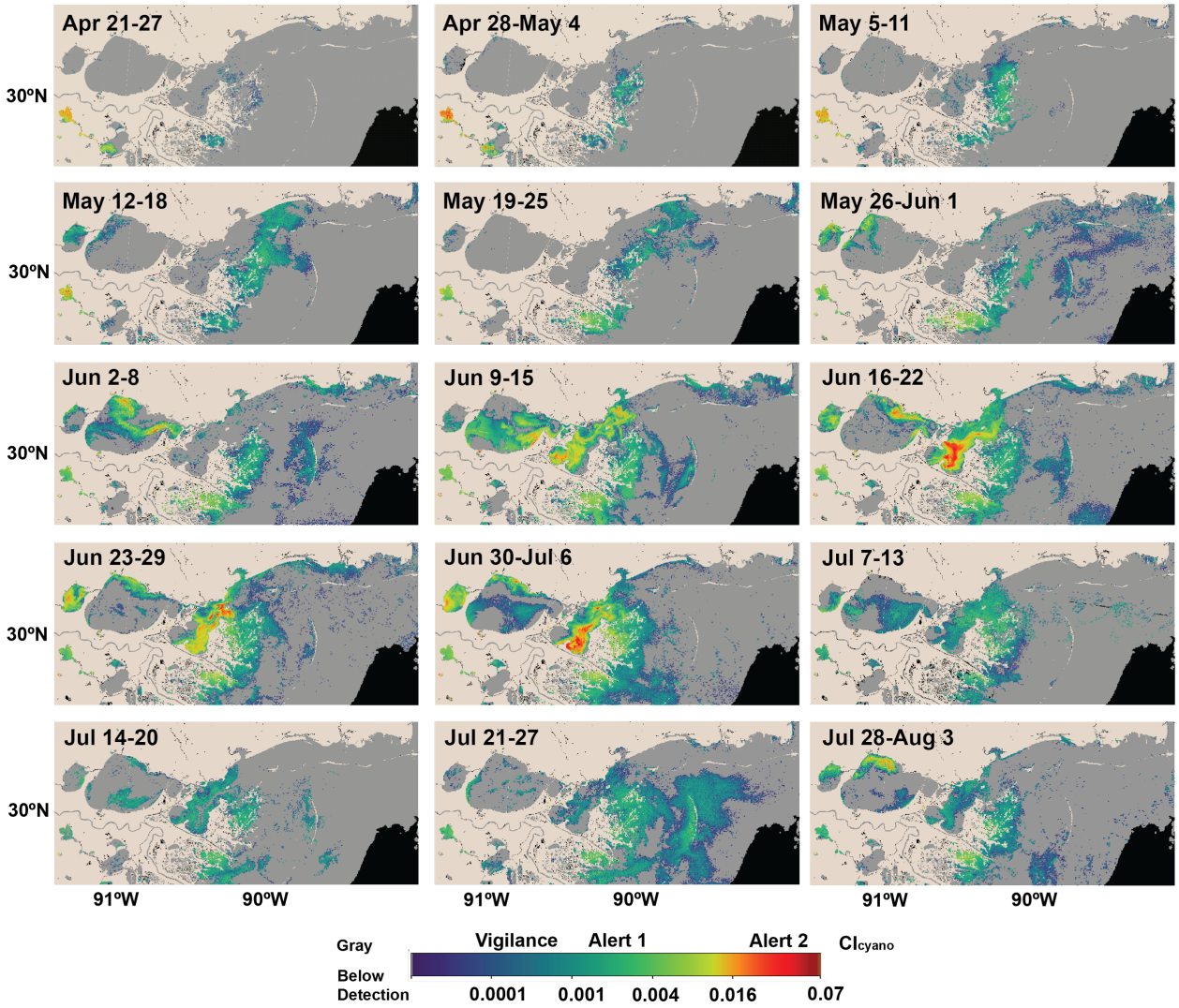

Apr 21-27
Apr 28-May 4
May 5-11
May 12-18
May 19-25
May 26-Jun 1
Jun 2-8
Jun 9-15
Jun 16-22
Jun 23-29
Jun 30-Jul 6
Jul 7-13
Jul 14-20
Jul 21-27
Jul 28-Aug 3
30°N
91°W
90°W
Gray
Below Detection
Vigilance
Alert 1
Alert 2
CIcyano
0.0001
0.001
0.004
0.016
0.07

Figure 8

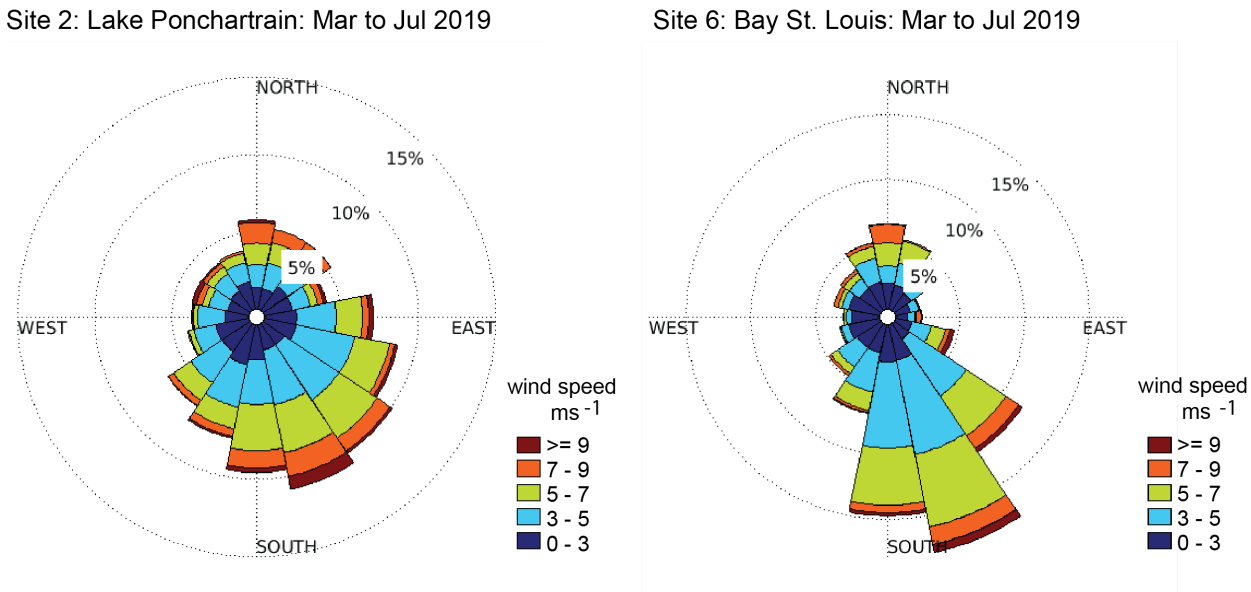
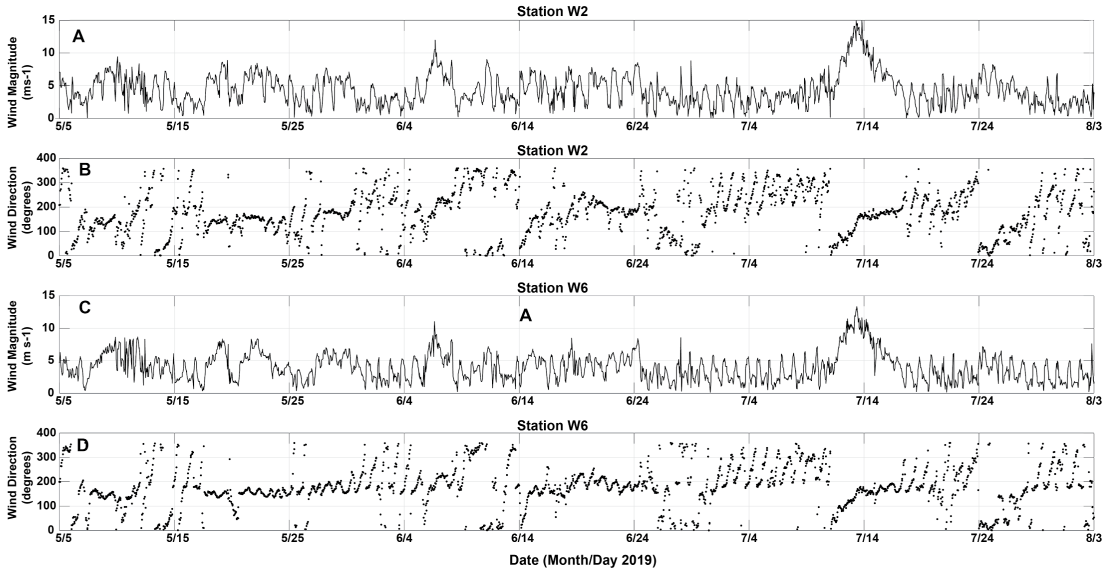
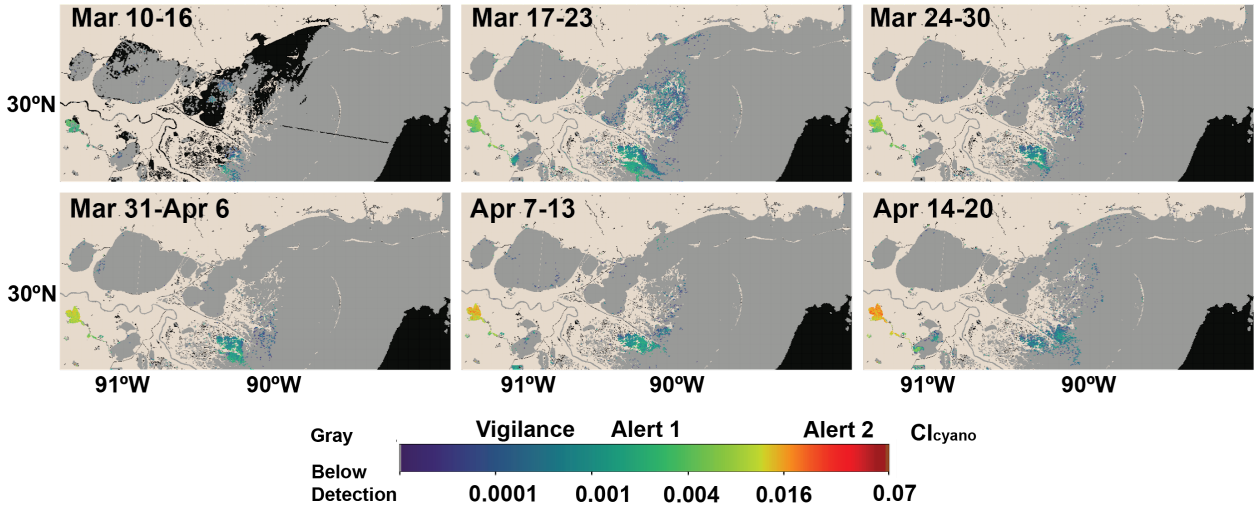


Figure 9



Appendix A



Appendix B

