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Detecting *Karenia brevis* blooms and algal resuspension in the western Gulf of Mexico with satellite ocean color imagery

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Abstract

Blooms of the toxic dinoflagellate, *Karenia brevis*, have had detrimental impacts on the coastal Gulf of Mexico for decades. Detection of *Karenia brevis* blooms uses an ecological approach based on anomalies derived from ocean color imagery. The same anomaly product used in Florida produces frequent false positives on the Texas coast. These failures occurred during wind-driven resuspension events. During these events resuspension of benthic algae significantly increases chlorophyll concentrations in the water, resulting in confusion with normal water column phytoplankton, such as *Karenia*. A method was developed to separate the resuspended chlorophyll from the water column chlorophyll, decreasing the false positives used with the detection method.

Keywords: Anomaly; Chlorophyll; Gulf of Mexico; Harmful Algal Bloom; *Karenia brevis*; Remote sensing; Resuspension; SeaWiFS; Texas

1. Background

Karenia brevis blooms are the principal cause of Harmful Algal Blooms (HABs) in the Gulf of Mexico (Kusek et al., 1999). *K. brevis* blooms cause massive fish kills, marine mammal kills and respiratory irritation in humans (Baden et al., 1995), and are also known to cause Neurotoxic Shellfish Poisoning (NSP) in various types of shellfish, which is hazardous to humans. Because they have such toxic effects, *K. brevis* blooms have been widely studied within the Gulf of Mexico in order to improve detection and monitoring. Tester et al. (1998) reported that the eastern gulf (the west coast of Florida) had experienced *K. brevis* blooms 26 out of the previous 27 years, and there has been a bloom reported every year since 1998. Because of the frequency of blooms on the west Florida shelf there has been an extensive HAB monitoring program in place for years in that region. For western portions of the gulf (the Texas coastline), only three bloom events were reported from 1935 to 1986. However, from 1986 to the

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present, Texas had three documented major bloom events in 1986, 1997 and 2000 (Magaña et al., 2003) and an apparently short lived (one positive cell count reported in October at Brazos Santiago Pass and one positive cell count in November at Sabine Pass) bloom in October and November of 1999 (Villareal and Magaña, 2001). The change indicates that the frequency and severity of Texas *K. brevis* blooms may be increasing (Magaña et al., 2003). There is no regular monitoring by state agencies in Texas. The limited sampling available outside of the bays is research-driven and is not useful as an early warning for *K. brevis* events. *K. brevis* cell count sampling in the bays occurs in Texas only after a probable bloom has been reported to the Texas Parks and Wildlife Division (TPWD) or Texas Department of Health, and sampling may occur only in economically important areas, such as shellfish beds, so the number of Texas blooms may be underestimated (Fig. 1).

1.1. History

Remote sensing techniques have been used to investigate *K. brevis* since 1978, when remote sensing, with an aircraft-based ocean color sensor, was first shown to detect discoloration associated with a bloom off the coast of southwest Florida (Muller, 1979). With the launch of the Coastal Zone Color Scanner (CZCS) in 1978, the potential has existed to detect HABs from satellite observations. CZCS operated from November 1978 to June 1986, and was used by researchers to examine *K. brevis* blooms during this time (Haddad, 1982). Since September 1997, when the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) became operational, near real time monitoring for *Karenia* has been possible with ocean color satellite imagery. SeaWiFS, ocean color data has become an important tool in monitoring for *K. brevis*, including the ability to provide alerts and forecasts to public health and coastal resource managers through a regular production of bulletins (Stumpf et al., 2003; Tomlinson et al., 2004).

Satellite monitoring programs, such as the one involved with SeaWiFS cannot be used to replace field sampling programs, but can complement them. Field sampling efforts incur tremendous costs in man hours and ship time. Directing field sampling efforts to dynamic areas that are likely to have a bloom or some other oceanographic phenomenon would be advantageous to managers and researchers. SeaWiFS is able to detect such features on a regular basis with potential daily revisits depending on cloud cover. SeaWiFS has a nominal 1.1 km field of view (pixel size) and a swath of over 2000 km in width allowing a synoptic view of a relatively large area.

2. Methods

2.1. Standard anomaly method

Sea surface temperature (SST) anomalies have been used to detect changes in the oceans, such as the presence of an El Niño, upwelling events, and climate predictions (Goddard et al., 2001). The change detection concepts used for temperature anomalies can also be employed with chlorophyll anomalies. The Gulf of Mexico is an oligotrophic body of water, with a relatively low background chlorophyll concentration. When there is a bloom, a rapidly increasing concentration of phytoplankton, in the Gulf of Mexico, it is easily seen in satellite imagery. This is because the chlorophyll from a typical bloom, such as a *Karenia* bloom, can have chlorophyll concentrations much higher than the typical background concentrations.

SeaWiFS imagery was processed using the SeaDAS 4 software. For atmospheric correction, the chlorophyll algorithm of Stumpf et al. (2000) was implemented, as it appears to give more consistent results in the Gulf of Mexico. New chlorophyll anomalies are then generated in order to detect possible *Karenia* blooms. To determine the anomaly, the mean chlorophyll is first determined for the 2 months ending 2 weeks before the current day (Tomlinson et al., 2004). The current day SeaWiFS image is then subtracted from this 2-month running mean to create the anomaly, with positive anomalies indicating a new phytoplankton bloom. The 2-week lag between the 60-day mean and the current day image is necessary in order to reduce the likelihood that a persistent and stationary bloom will skew the mean, and reduce the detection capability. Areas within the resultant image that exhibit a change in chlorophyll concentration greater than or equal to 1 $\mu g\ L^{-1}$, during the *K. brevis* season, are considered to be probable *Karenia* blooms. Exceptions are made

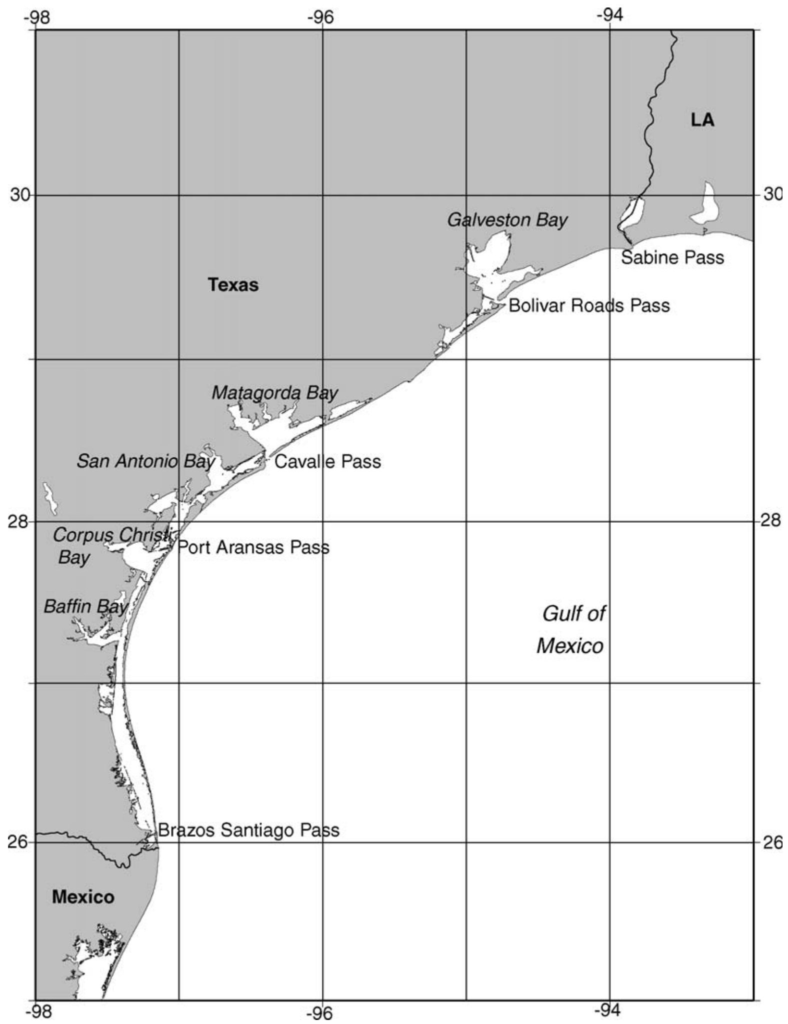


Fig. 1. Map of the Texas coastline showing the study area.

in areas with significant river discharge, as these areas rarely have *Karenia* blooms and frequently have diatom blooms. Non-toxic algal blooms do occur in this region and as a result field sampling is necessary to positively identify the chlorophyll anomalies as HABs. Other data, SST and wind, is also used to refine the detection (Stumpf et al., 2003). Tomlinson et al. (2004) showed that along the panhandle and south-western coasts of Florida, this method is about 80% effective in recognizing *K. brevis* blooms during the bloom season.

This same technique was then applied to the western portion of the Gulf of Mexico but the initial results were unsatisfactory, since there was an abundance of anomalies for areas where no bloom was reported. This discrepancy may be due to infrequent in situ sampling in Texas (Villareal and Magaña, 2001), since event response sampling may miss blooms that routine monitoring programs, such as the one deployed in Florida, will catch. With the absence of a routine monitoring system for Texas waters, it is possible that blooms can occur and be undetected. If a bloom occurs offshore in the presence of offshore winds, dead fish and noxious aerosols will not reach the shore, preventing the HAB event from ever being documented. However, we presume, conservatively, that anomalies occurring in a period where no HAB is reported are false positives.

Many of the HAB anomalies coincided with resuspension events along the Texas continental shelf. The coastal waters of Texas have high suspended sediment loads in the surface waters, particularly in the northern portion of the state where riverine runoff is high. Manheim et al. (1972) found that the surface sediment load was still on the order of 1 mg L^{-1}. These are typical suspended sediment loads, and can become significantly higher during periods of extreme resuspension events. These events can also transport benthic algae and sediments into the water column (Nelson et al., 1999). Benthic chlorophyll that is resuspended to within one optical depth of the surface will be detected by satellite chlorophyll measurements and add to existing planktonic chlorophyll concentrations. Total benthic chlorophyll per unit area can exceed the chlorophyll-a concentration in the integrated water column (Radziejewska et al., 1996; Cahoon and Laws, 1993; Cahoon et al., 1990). Therefore, during resuspension events, benthic chlorophyll may dominate the observed chlorophyll concentration. This addition of resuspended benthic chlorophyll into the system can produce a new chlorophyll anomaly unrelated to the presence of *K. brevis*, a pelagic dinoflagellate.

2.2. Corrected chlorophyll anomaly

In order to remove false positive HAB anomalies caused by resuspended sediments, a method is required to distinguish resuspended materials from the chlorophyll-a concentrations that were present in the water column prior to the resuspension event. To do this we use more of the spectral information available from SeaWiFS. The SeaWiFS sensor has eight spectral bands. Six of these bands are in the visible light spectrum, and are centered in the following wavelengths: 412 nanometers (nm), 443 nm, 490 nm, 510 nm, 555 nm, 670 nm. The remaining SeaWiFS bands lie in the near infrared (NIR) and are used for atmospheric correction.

Backscattered light is directly correlated with the concentration of inorganic sediments. For the sediment concentration levels found in this environment, backscatter can be linearly approximated by the reflectance in red wavelengths (Stumpf and Pennock, 1989).

Reflectance in the 670 nm band (R_{670}), where absorption is much greater than backscatter, can be approximated by the following equation:

$$R_{670} \propto \frac{\mathrm{bb}_{670}}{a_{670}} \tag{1}$$

where bb_{670} and a_{670} are defined as the backscatter and the absorption of the 670 nm band, respectively. Backscatter is defined by the following equation:

$$\mathrm{bb}_{670} = \mathrm{bb}_\mathrm{w} + \mathrm{bb}_\mathrm{s} + \mathrm{bb}_\mathrm{p} \tag{2}$$

where the subscripts of w, s, and p indicate contributions to backscatter from: water, sediment, and plankton, respectively. The backscatter is related to sediment concentration, S, by:

$$\mathrm{bb}_\mathrm{s} = \mathrm{bb}'_\mathrm{s} \times S \tag{3}$$

where bb'_s is the specific backscatter coefficient for sediment. Absorption at 670 nm is defined as following:

$$a_{670} = a_\mathrm{w} + a_\mathrm{g} + a_\mathrm{d} + a_\mathrm{p} \tag{4}$$

where the subscripts of w, g, d, and p indicate contributions from: water, colored dissolved organic material (CDOM), detritus, and plankton, respectively. In general, $a_\mathrm{w} \gg a_\mathrm{g} + a_\mathrm{d} + a_\mathrm{p}$, and $\mathrm{bb}_\mathrm{s} \gg \mathrm{bb}_\mathrm{w} + \mathrm{bb}_\mathrm{p}$, so that reflectance is proportional to $\mathrm{bb}_\mathrm{s}/a_\mathrm{w}$. By combining this proportionality with Eq. (3), we see that the red reflectance (R_{670}) is a surrogate for sediment concentration (S). At shorter wavelengths, the total absorption is not a constant, so reflectance cannot be used to approximate the sediment concentration. As the sediment load in the water column increases, the reflectance in the 670 nm wavelength will increase.

In order to calculate a way to measure the amount of resuspension in a given image, a 670 reflectance anomaly is created, in the same way as the chlorophyll anomaly described earlier. This method would flag turbid river plumes as resuspension events. However, the Texas coast has small plumes from its bays and rivers, limiting this problem to periods after extensive rains, tropical storms or hurricanes.

With a method in place to estimate the resuspension at a given time and location, it becomes possible to estimate the amount of chlorophyll that is introduced into the water column as a result of resuspension events. Benthic chlorophyll should resuspend at about the same rate as sediment, so it was assumed that a linear relationship exists between the chlorophyll anomaly and the resuspended sediment anomaly. To determine this relationship, several cloud free images were selected, and a linear regression was calculated between the 670 reflectance anomaly and the chlorophyll anomaly for each image. The average slope of the regression was approximately 200 μg sr L^{-1} and this slope was tested empirically by comparing the effects that different regressions had on imagery. The slope that yielded the most accurate results was approximately 200 (Fig. 2). Therefore the amount of resuspended benthic chlorophyll is estimated as:

$$\text{Resuspended Benthic Chlorophyll}\,(\mu\text{g}\,\text{L}^{-1}) = \text{Rrs}_{670}(\text{sr}^{-1}) \times M \qquad (5)$$

where $M = \Delta\text{chl}/\Delta 670 = 200$ μg sr L^{-1}.

Subtracting this resuspended chlorophyll from the total amount of chlorophyll in the system allows for an estimate of how much chlorophyll was planktonic during a resuspension event. However, for our application, the difference of the chlorophyll anomaly, which is the total ''new'' chlorophyll in the water and the resuspended chlorophyll, gives the new planktonic chlorophyll bloom through the adjusted chlorophyll anomaly:

$$\text{Adjusted Chl Anomaly}\,(\mu\text{g}\,\text{L}^{-1}) = \text{Chl Anomaly}\,(\text{mg}\,\text{L}^{-1}) - \text{Resuspended Benthic Chl}\,(\text{mg}\,\text{L}^{-1}) \qquad (6)$$

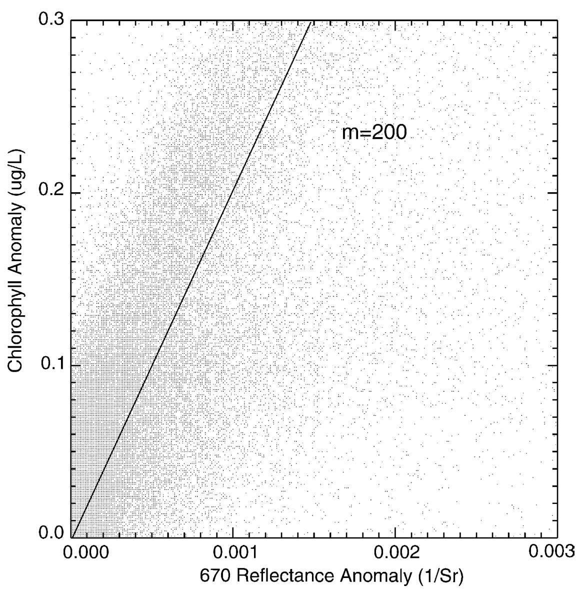


Fig. 2. Linear regression of the chlorophyll anomaly to the 670 reflectance anomaly for a single image. This relationship was used in order to correct the chlorophyll anomaly for resuspension.

3. Results and discussion

Visual analysis was performed on SeaWiFS images from 1998 to 2002, both before and after the resuspension correction was applied. The adjusted chlorophyll anomaly method successfully removed many of the unvalidated anomalies that were present before the correction. There was a large and persistent bloom of *K. brevis* documented in the summer/fall of 2000. This was the only documented major *K. brevis* bloom during the time period of the study, and this period was examined independently of the non-bloom years. In non-bloom periods, 391 images were examined and, 130 images or 33.2% had anomalies before the correction. After the correction, 75 images, or 19.1%, were flagged for blooms. The correction eliminated 43% of the days containing anomalies. In the 3-year period when there were no HABs reported, there were no anomalies reported in over 80% of the imagery (see Fig. 3) after correction.

K. brevis typically blooms in the Gulf of Mexico in the summer/late fall. Therefore the method was applied to the Texas shelf from June 1 to November 30. The method does not prove useful in the spring. Nearly every day is flagged as a bloom during this period as this is typically when phytoplankton biomass increases rapidly due to favorable light, temperature, and nutrient conditions.

3.1. 1999 HAB event

Cell counts from Villareal and Magaña (2001) showed that there were cell counts in the Texas coast from a short lived bloom in October to November in 1999. Cell counts were documented in Sabine Pass, Bolivar Roads Pass, and Brazos Santiago Pass of 2500, 37,500, and 10,000 cells L^{-1}, respectively. Tester et al. (1998) showed that the minimum detection

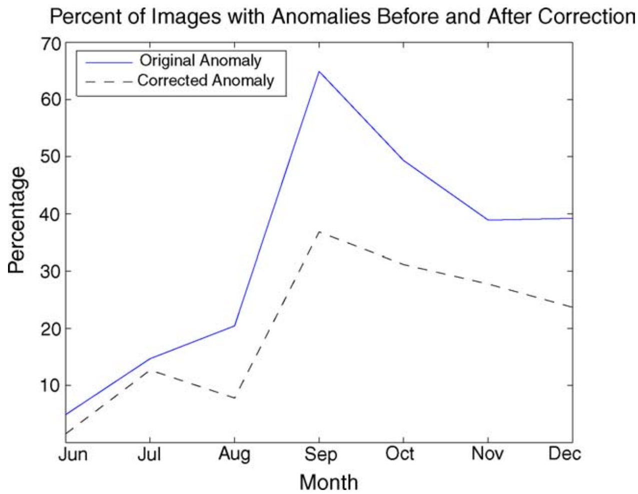


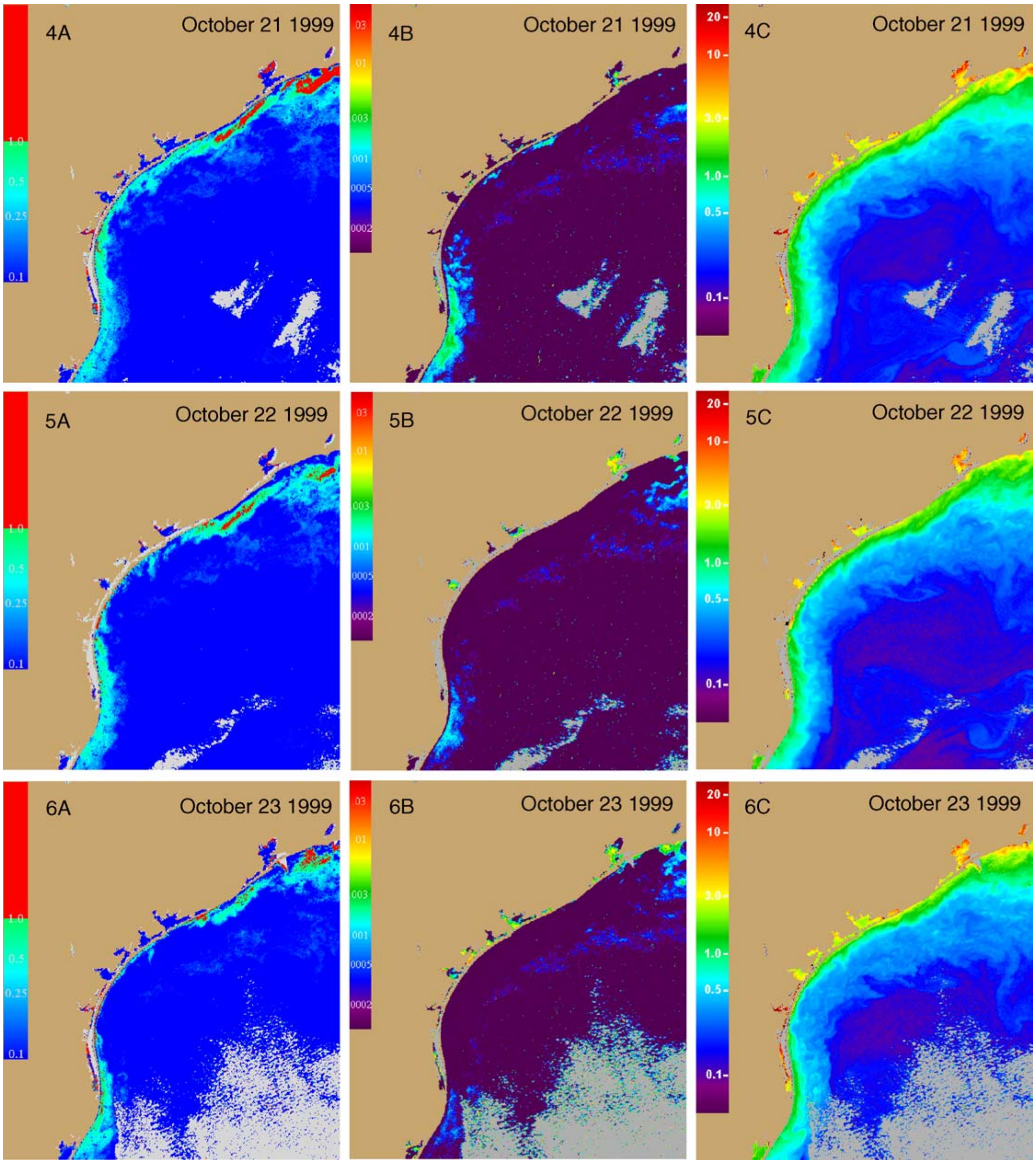
Fig. 3. Illustrates the reduction of false positives by month between the corrected chlorophyll anomaly and the original chlorophyll anomaly.

limit for detecting *Karenia brevis* from satellite imagery is 50,000 cells L^{-1}. However, the limited field sampling cannot address the complete spatial extent and intensity of the bloom during this time frame. The imagery showed several anomalies along much of the Texas coastline in these 2 months. While the highest reported cell counts are too low to be detected from a remote sensing perspective it could be possible that there was a much greater bloom than verified by field data. The imagery from October 21 to 23 show an anomaly on the northern coast of Texas, and a smaller anomaly in the southern coast that may be indicative of a much larger bloom than was documented (see Figs. 4–6). There was a fish kill reported to the TPWD in late October 1999 in the area surrounding Brazos Santiago Pass (Villareal et al., 2000). In addition, all the coastal sampling was within the 9 nautical mile (15 km) state territorial waters. The anomalies noted in Figs. 4–6 appeared to be further offshore, and would not have been detected by the field sampling.

3.2. 2000 HAB event

As was previously mentioned there was one large and persistent bloom reported off Texas during our study period, starting in August, 2000 and persisting until November, 2000. This section will discuss how well retrospective analysis did in documenting the bloom during this period. On August 11, the first report of a possible red tide was made when local fisherman noticed thousands of black drum south–southeast of Sabine Pass (northeastern coast of Texas) by the Louisiana border. The TPWD investigated and on August 14 discolored water in the region was observed during an over flight. The discolored water was positively identified as *K. brevis*. During this time of the year, general circulation along the Texas coast is from north to south (Cochrane and Kelly, 1986). This alongshore circulation pattern transported *K. brevis* cells southward down the coast. *K. brevis* was reported in Galveston Bay on August 31, Matagorda Bay by September 18, and Corpus Christi Bay on September 22. By October 3, the bloom had reached San Antonio Bay. The bloom persisted in localized regions, such as back bays and estuaries along the coast, until November 8, when there were no longer positive cell counts reported. The blooms were tracked through bimonthly in situ sampling (Villareal and Magaña, 2001).

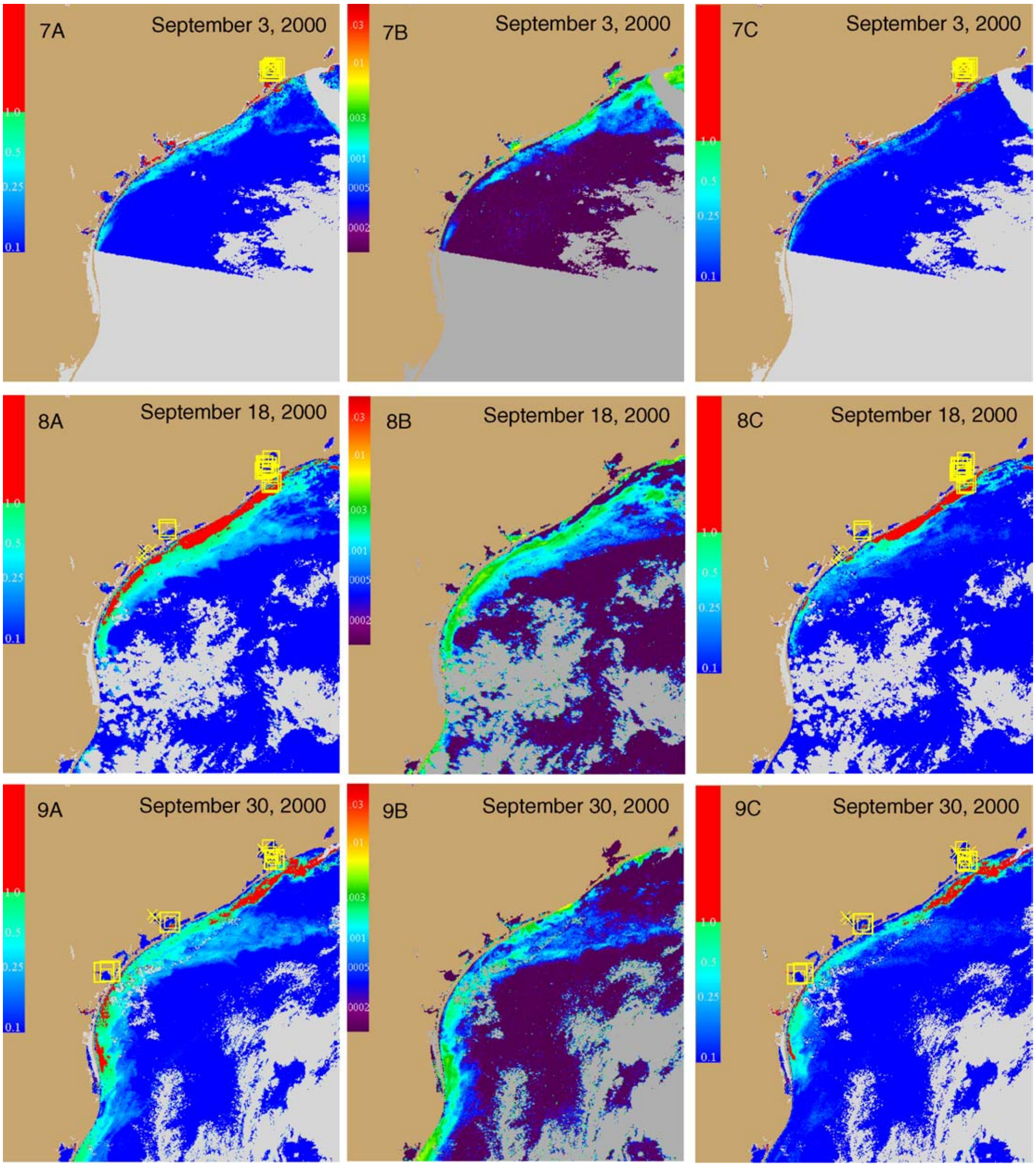
Corrected anomaly images and cell counts were examined for this period of time. By August 31, a small anomaly developed south of Galveston Bay. On September 3, 3 days after, the first positive cell counts were recorded in the same general area (Fig. 7). By September 12, a large anomaly had developed from Galveston Bay to Matagorda Bay. This was the first point that cell counts above 50,000 cells L^{-1} were recorded. 50,000 cells L^{-1} is the limit of satellites to detect *K. brevis* blooms (Tester et al., 1998). By



Figs. 4–6. Figs. 4A, 5A, and 6A show the corrected chlorophyll anomalies, where the red areas indicate potential Karenia blooms. Figs. 4B, 5B, and 6B show the remote sensing reflectance at the 670 nm wavelength. This was used as a surrogate for resuspension and shows little to no resuspension in the area that has been flagged for a bloom. Figs. 4C, 5C, and 6C show the standard chlorophyll imagery. The anomaly imagery clearly shows the elevated chlorophyll that can also be seen in the chlorophyll imagery.

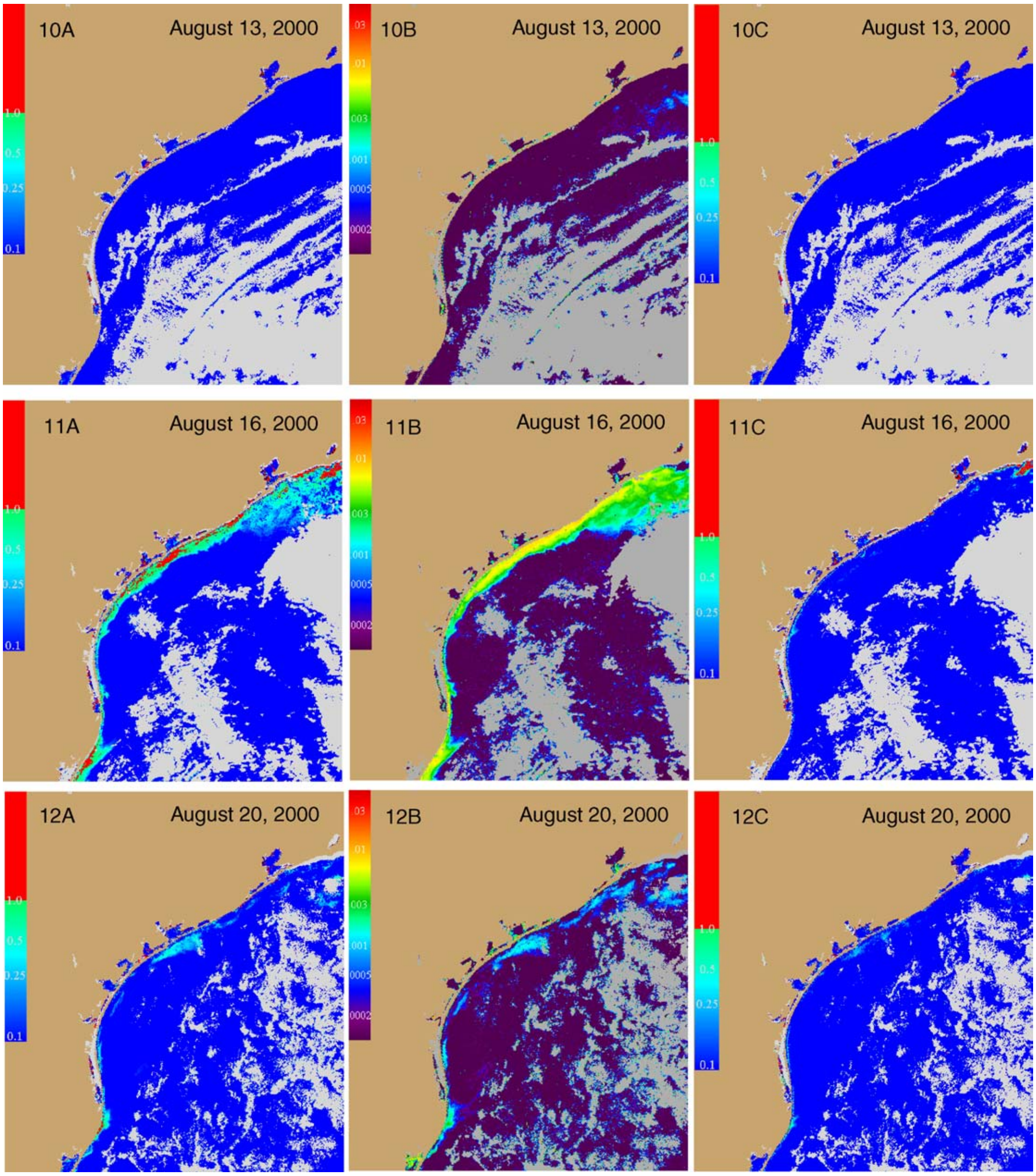
September 18, the anomaly reached its largest area from Galveston Bay in the north to Matagorda Bay in the south (Fig. 8). Anomalies persisted in the imagery until October 18, when cloud cover precluded usable imagery. This extended until November 5 when anomalies had ceased.

Overall, the retrospective analysis using the adjusted anomaly method proved successful in



Figs. 7–9. These images were taken during the Karenia bloom of 2000. Fig. 7A shows the standard chlorophyll anomaly. The boxes indicate the position of positive cell counts. There is a small anomaly located in the vicinity of Bolivar Roads Pass. Fig. 7B shows the 670 reflectance anomaly, used as a surrogate for suspended sediment concentrations. Fig. 7C shows the corrected chlorophyll anomaly; note that all anomalies in the original anomaly image are still visible. Fig. 8A shows the standard chlorophyll anomaly the ''×'' indicates samples with a cell count of 0. The corrected chlorophyll anomaly keeps the anomaly where it was positively identified (Bolivar Roads Pass to Cavalle Pass) but the anomaly disappears south of Cavalle Pass. There were no cell counts available to verify this. Fig. 9A shows the further spread of the bloom. There were no cell counts available south of Baffin Bay to confirm or deny the anomaly present in the area.

monitoring the entire coastline for the spread of the bloom. Most of the in situ cell counts were taken in the back bays and estuaries of the Texas coastline, where the majority of the state's shellfish beds are located. The remote sensing anomaly techniques are not efficient in these types of estuarine environments, as



Figs. 10–12. Fig. 10 imagery taken just prior to the pass of Tropical Storm Beryl. Resuspension (10B) is very low and no chlorophyll anomaly is present in either the uncorrected (10A) or corrected imagery (10C). Fig. 11A–C was from the day following the pass of the storm. Resuspension (11B) is elevated, causing anomalies in the uncorrected image (11A), but these anomalies are removed by the correction (11C). Fig. 12A–C shows a return to ''normal'' conditions, with low resuspension and no anomalies present.

we are limited by the 1 km field of view of the SeaWiFS sensor.

The adjusted chlorophyll method did not take away any of the confirmed anomalies. In some cases the extent of the anomaly was reduced in the southern part of the region. *K. brevis* was not reported south of Baffin Bay. The region was initially flagged in several images during the period of the bloom. After the region was corrected for resuspension these anomalies were removed in most cases until mid-October. Fig. 9

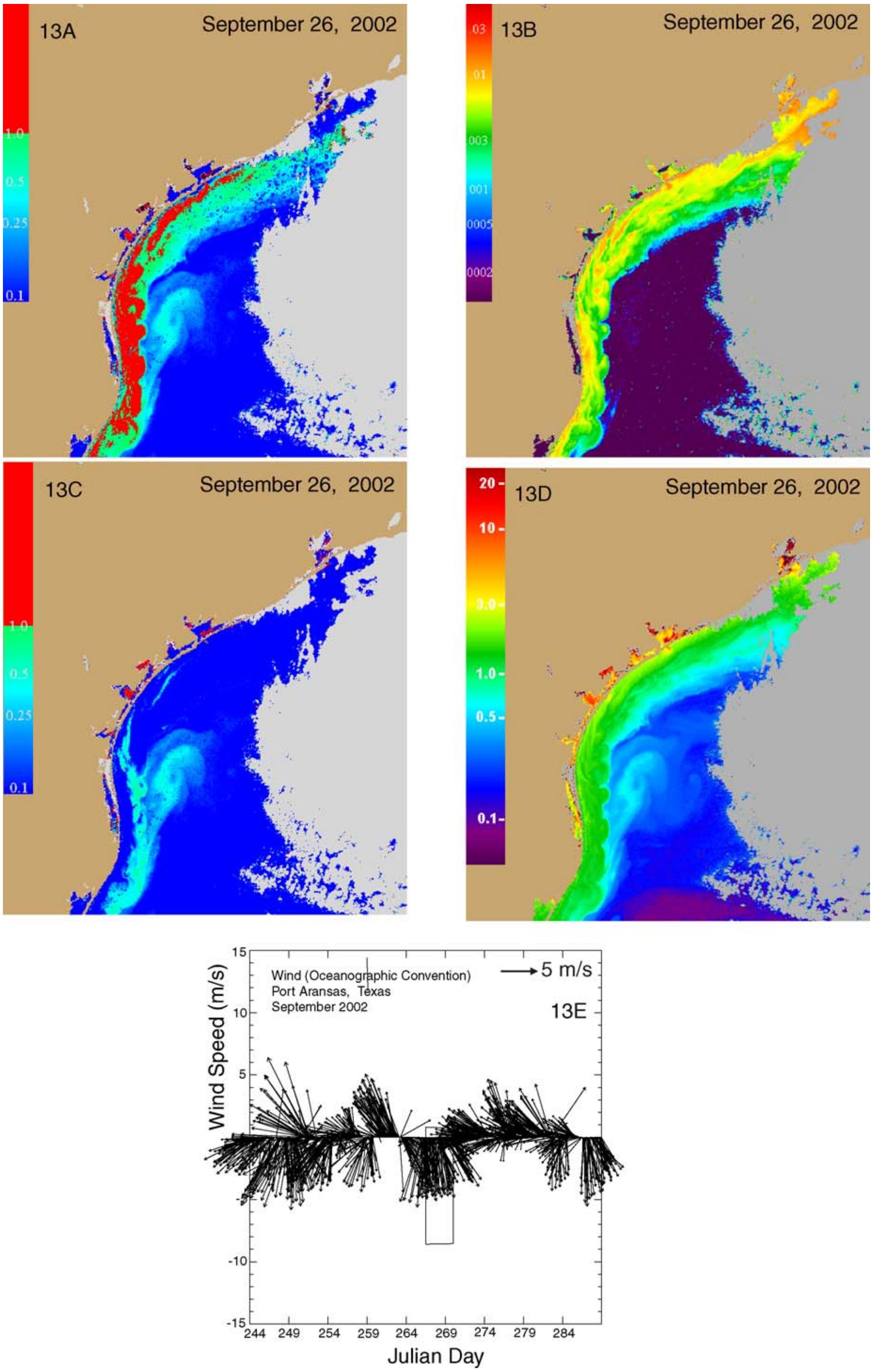


Fig. 13. Image 13A shows the original chlorophyll anomaly from September 26, 2002, with red areas indicating potential blooms. Fig. 13B shows the 670 reflectance anomaly, which indicates very high rates of resuspension, which is misinterpreted as chlorophyll (13D). After resuspension is accounted for the anomalies disappear (13C). Fig. 13E shows the wind distribution from Port Aransas, TX. A wind of only 7 m/s was responsible for generating the large anomaly illustrated in 13A, demonstrating the critical need to correct for resuspension.

illustrates such a case. The anomaly traveled from the south down the coast. There were no cell counts above the threshold of 50,000 cells L^{-1} available to confirm or deny this potential bloom at the time. It should be noted that the area south of Baffin Bay to Brownsville is sparsely populated and little field data was available for the region, making it impossible to say whether the method was effective in this portion of the coast.

3.3. Tropical Storm Beryl example

A time series of a resuspension event is illustrated in Figs. 10–12. The image in Fig. 10 shows normal conditions just before the pass of Tropical Storm Beryl. T.S. Beryl made landfall about 30 miles south of the Texas–Mexico border the night of August 15, 2000, with sustained winds of approximately 50 knots. This would classify as a strong resuspension event. On August 15 there were typical conditions, without elevated chlorophyll concentrations, and relatively low resuspension. On August 18 there was a high concentration of resuspended materials that were introduced into the water column, as illustrated in the 670 reflectance anomaly (Fig. 11B). Note the presence of an anomaly that developed in the image in Fig. 11A before the correction, and the removal of the anomaly after the correction as seen in Fig. 11C, which produces results consistent with the phytoplankton chlorophyll anomaly found in Fig. 10A. By August 20 conditions returned back to normal, with low resuspension rates and no chlorophyll anomalies (Fig. 12). The August 20 image also indicates that the resuspension did not cause development of a new plankton algal bloom.

3.4. Additional resuspension event

There are many smaller resuspension events in Texas that are not due to major events like tropical storms. A shift in wind direction can be enough of a forcing function to cause a resuspension event. An example of one such resuspension event is illustrated in Fig. 13. Fig. 13A shows the chlorophyll anomaly from September 26, 2002 before the image was corrected for resuspension. Fig. 13B shows the 670 reflectance anomaly. Fig. 13C shows the chlorophyll anomaly after the image has been adjusted for resuspension. There were extensive anomaly areas offshore before the adjustment, and the anomalies were totally removed after the image was corrected for resuspension. These anomalies are implied when observing the standard chlorophyll concentration, as seen in Fig. 13D. This example illustrates that the forcing function behind a resuspension event does not need to be as dramatic as a tropical storm or a hurricane. Fig. 13E shows the graph of wind data from a National Oceanic and Atmospheric Administration (NOAA) Coastal-Marine Automated Network (C-MAN) buoy located at Port Aransas, TX. The graph is for the entire month of September. On September 24 (Julian Day 267), 2 days before the date of the image, the winds began blowing from the north towards the south with a speed of approximately 7 m/s. While this is slightly above the mean wind speed for this area it is by no means a meteorological anomaly and is a fairly regular occurrence. It is important to note that not every 670 reflectance anomaly is as a direct result of resuspension. River plumes can cause reflectance anomalies, but rivers in Texas are relatively small and will produce localized anomalies in the 670. It is possible that some blue-green algae blooms can produce 670 anomalies. 670 reflectance anomalies that occur along large portions of the coast are for the most part as a direct result of resuspension.

4. Conclusions

Overall the adjusted chlorophyll method proved successful. Known blooms were identified in imagery during the 2000 bloom. Unconfirmed anomalies were eliminated by over 40% during non-bloom periods. Unconfirmed anomalies that remained after the correction can be attributed to a number of possibilities. The Texas coast has a higher background chlorophyll concentration than Florida does in non-bloom conditions, implying that the region is a more productive area than is Florida (Muller-Karger et al., 1991). Therefore a strong possibility exists that many of these remaining anomalies could be from other phytoplankton, such as a bloom of non-toxic diatoms. This monitoring method does not work reliably east of Galveston Bay, as the Mississippi River plume dominates the optical properties of this water and anomalies must be viewed with a high degree of skepticism. The method worked well for the remaining portion of the Texas coastline, from Galveston Bay to off shore of Laguna Madre.

Adjusting the chlorophyll anomaly for resuspension produces reasonable and consistent HAB detection for this coast. It may also provide improvements in HAB detection along the Florida coast as well. The method also provides insights into the blooms that are exclusively planktonic.

Ideally the western Gulf of Mexico will be incorporated into a satellite HAB monitoring system. Stumpf et al. (2003) describes in detail a system deployed by NOAA to monitor HABs in the gulf using anomaly methods as were described in this paper. In the future the same monitoring system will be incorporated to the Texas coast.

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