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Monitoring *Karenia brevis* blooms in the Gulf of Mexico using satellite ocean color imagery and other data

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Abstract

Harmful algal blooms (HABs) of *Karenia brevis* are a recurrent problem in the Gulf of Mexico, with nearly annual occurrences on the Florida southwest coast, and fewer occurrences on the northwest Florida and Texas coasts. Beginning in 1999, the National Oceanic and Atmospheric Administration has issued the Gulf of Mexico HAB Bulletins to support state monitoring and management efforts. These bulletins involve analysis of satellite imagery with field and meteorological station data. The effort involves several components or models: (a) monitoring the movement of an algal bloom that has previously been identified as a HAB (type 1 forecast); (b) detecting new blooms as HAB or non-HAB (type 2); (c) predicting the movement of an identified HAB (type 3); (d) predicting conditions favorable for a HAB to occur where blooms have not yet been observed (type 4). The types 1 and 2 involve methods of bloom detection requiring routine remote sensing, especially satellite ocean color imagery and in situ data. Prediction (types 3 and 4) builds on the monitoring capability by using interpretative and numerical modeling. Successful forecasts cover more than 1000 km of coast and require routine input of remotely sensed and in situ data.

The data sources used in this effort include ocean color imagery from the Sea-Viewing Wide Field-of-View Sensor/OrbView-2 satellite and processed using coastal-specific algorithms, wind data from coastal and offshore buoys, field observations of bloom location and intensity provided by state agencies, and forecasts from the National Weather Service. The HAB Bulletins began in coordination with the state of Florida in autumn of 1999 and included *K. brevis* bloom monitoring (type 1), with limited advisories on transport (type 3) and the detection of blooms in new areas (type 2). In autumn 2000, we improved both the transport forecasts and detection capabilities and began prediction of conditions favorable for bloom development (type 4). The HAB Bulletins have had several successes. The state of Florida was advised of the potential for a bloom to occur at the end of September 2000 (type 4), and the state was alerted to the position of blooms in January 2000 and October 2001 in areas that had not been previously sampled (type 3). These successful communications of HAB activity allowed Florida

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agencies responsible for shellfish management and public health to respond to a rapidly developing event in a timely, efficient manner.

Keywords: Chlorophyll; Florida; Forecasts; Gulf of Mexico; Harmful algae; *Karenia brevis*; Remote sensing; SeaWiFS

1. Introduction

Karenia brevis, a toxic dinoflagellate, is the most common cause of harmful algal blooms (HABs) in the Gulf of Mexico (Fig. 1), impacting all five Gulf coast states. *K. brevis* produces brevetoxins responsible for neurotoxic shellfish poisoning (NSP), deaths of marine mammals and large numbers of fish, and human respiratory irritation (Tester and Steidinger, 1997). In US waters, blooms occur in most years along the Florida west coast. While less frequent in Texas, blooms have occurred there in 6 of the last 7 years (Buskey et al., 1996; Villareal, personal communication). The first documented event in Alabama, Mississippi and Louisiana occurred in 1996 (Dortch et al., 1998; Pennock, personal communication). Because of

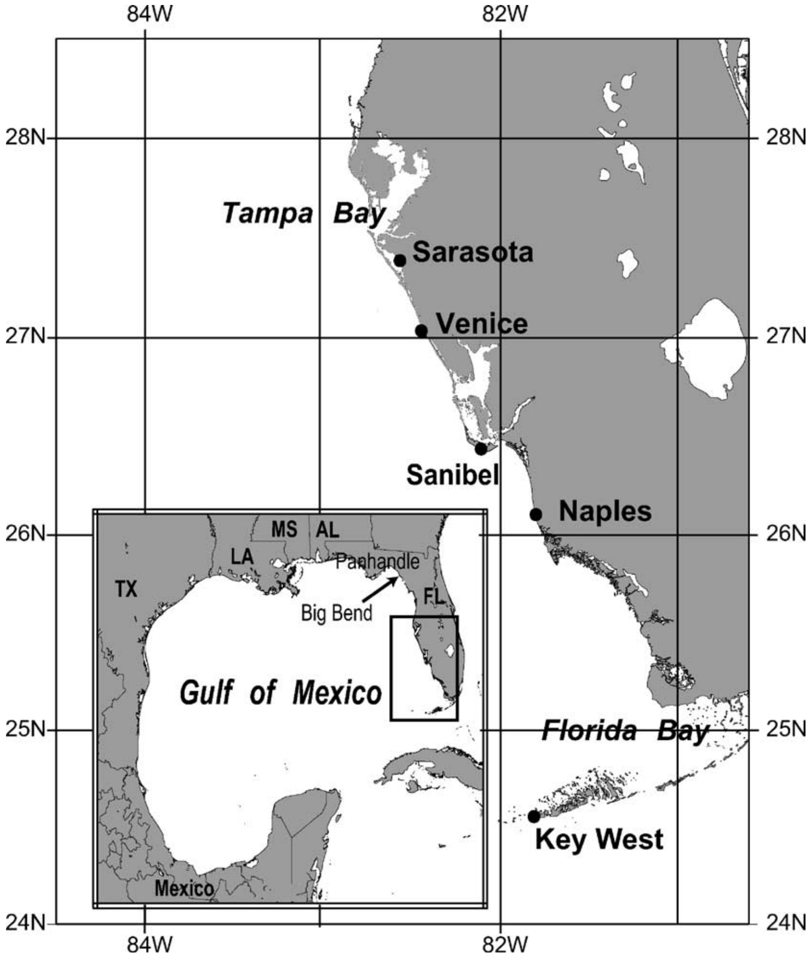


Fig. 1. Location of areas in the Gulf of Mexico and southwest Florida coast.

the threat of NSP, all Gulf states close shellfish beds in the presence of >5 cells ml^{-1}. Florida and Alabama conduct some routine monitoring, but all the states monitor in response to indicator events, such as fish kills, discolored water, or respiratory distress. Monitoring is still problematic. Florida alone has more than 1000 km of coastline at risk for HABs, making improved monitoring a necessity for effective resource management. In particular, information is needed that can allow managers to assess the extent of HABs and anticipate how to deploy during an event.

Remote sensing has been proposed as a means of detecting and characterizing the location and extent of HABs because of the potential to observe large areas synoptically (Cullen et al., 1997; Tester and Stumpf, 1998; Schofield et al., 1999). While the term "red tide" is often used to describe these HABs, *K. brevis* blooms cause water discoloration varying from mahogany to yellow depending on the concentration of the organism and the presence of other pigments and phytoplankton species (Steidinger and Haddad, 1981; Millie et al., 1995). The states use observers on aircraft (when practical) to find and delineate discolored water when HABs are known or believed to be present. Mueller (1979) first showed that multi-spectral imagery (collected from aircraft) can detect a bloom containing *K. brevis*. Steidinger and Haddad (1981) demonstrated the potential of satellite sensors with the Coastal Zone Color Scanner (CZCS). This experimental sensor, which collected data between 1978 and 1986, was designed to monitor phytoplankton pigment concentrations. CZCS first showed a major bloom of *K. brevis* in 1978 as a high-chlorophyll, discolored water feature. Subsequently, CZCS imagery was used to estimate the extent of blooms for additional analyses (e.g. Vargo et al., 1987). However, routine monitoring was not practical with that sensor because of the delays involved in collecting and processing the imagery at that time.

Other satellites, such as the Advanced Very High Resolution Radiometer (AVHRR), have an operational real-time capability. The AVHRR, normally used for sea surface temperature mapping, has two low-sensitivity, visible channels that can be used to find large blooms of phytoplankton that scatter light or occur in highly turbid water (Stumpf and Tyler, 1988; Gower, 1994; Brown and Yoder, 1994). However, *K. brevis* does not scatter light significantly (Carder and Steward, 1985) and rarely occurs in highly turbid water, so the AVHRR is not a suitable sensor for detection of these blooms. The AVHRR thermal data can aid in detecting movements of water masses associated with *K. brevis* blooms (Haddad, 1982; Tester et al., 1991; Tester and Steidinger, 1997).

After an 11-year hiatus, ocean color imagery again became available in September 1997, when the Sea-Viewing Wide Field-of-View Sensor ocean color sensor became operational. This sensor provides daily images of chlorophyll concentration and is useful for detecting patterns in ocean color within a region. In September 1999, the National Oceanic and Atmospheric Administration's (NOAA) CoastWatch program began acquiring imagery routinely for civil government applications, with HAB monitoring as a primary application. For government operations, SeaWiFS imagery must be purchased from OrbImage. This allows use in near real-time, while research and educational applications must wait 14 days for access to imagery.

As a result of the CoastWatch purchase, NOAA began to integrate the SeaWiFS satellite imagery with other datasets in order to support the states in monitoring for HABs in the Gulf, starting with Florida. The various datasets have been incorporated into "Harmful Algal Bloom Bulletins" that are distributed to state, federal and local officials responsible for sampling, monitoring, or responding to HABs in the Gulf of Mexico.

The ultimate goal of the bulletins is to provide both monitoring and forecasting information. Our effort has focused on four types of monitoring for HABs: monitoring existing blooms of *K. brevis* (type 1), detecting new outbreaks of *K. brevis* (type 2), forecasting transport of blooms to new locations (type 3), and predicting conditions favorable for HAB appearance at the coast prior to the outbreak (type 4). Due to the urgency of making information available to public health officials and the marine management community, the experimental methods here were implemented in the monitoring program after only a preliminary evaluation. This paper will report on the implementation of these analyses and their utility specifically in Florida over the first 3 years (1999–2001). In many applications, the methods are implemented in a monitoring effort only after a program of research and evaluation.

2. Methods

2.1. Satellite imagery

The SeaWiFS sensor is on OrbImage's OrbView-2 satellite and flies in a sun-synchronous polar orbit with overpasses at about 13:00 h local time every 1–2 days. The sensor has a nominal field-of-view of 1.1 km at nadir with six visible bands for ocean color measurements and two near-infrared bands for atmospheric correction. Typically, *K. brevis* blooms start in late summer and continue until mid-winter, although the duration varies considerably. NOAA obtains one image every 1–2 weeks during the non-bloom period of winter and spring. In mid-summer, images are obtained more frequently, and during a bloom one to three images are used each week.

Each image is processed with an atmospheric correction algorithm that includes a correction for water-leaving radiance caused by sediment in the near-infrared bands and a correction for absorbing aerosols (compensating for pollution or dust). Without this processing, chlorophyll concentrations are overestimated in more turbid water, particularly when resuspension occurs during the passage of autumn cold fronts. The NASA global chlorophyll algorithm overestimates in the eastern Gulf of Mexico, usually from two- to four-fold, necessitating a regional algorithm (Stumpf et al., 2000).

2.2. *K. brevis* HAB monitoring and detection

Chlorophyll is not a unique indicator for *K. brevis*, so we have sought a method for identifying or flagging high chlorophyll as *K. brevis*. Researchers have developed methods for detecting optically unique blooms such as those of coccolithophores and *Trichodesmium* spp. (Brown and Yoder, 1994; Subramaniam and Carpenter, 1994). Spectral discrimination of *K. brevis* with the six bands of SeaWiFS is unlikely. *K. brevis* and other dinoflagellates have similar pigments as diatoms and other phytoplankton found in the Gulf of Mexico (Millie et al., 1997). Optical discrimination, based on the relatively low backscatter of *K. brevis*, offers one approach (e.g. Carder and Steward, 1985; Cannizzaro et al., 2002), but may require water lacking particulate matter or other pigments (such as dissolved pigments).

The eastern Gulf of Mexico is an oligotrophic system with relatively low concentrations of chlorophyll. The spring diatom blooms described by Gilbes et al. (1996) lead to chlorophyll concentrations of only 1–3 $\mu g\,l^{-1}$, while background levels vary from 0.1 to $<1\ \mu g\,l^{-1}$ on the inner shelf. *K. brevis* blooms occur usually in the late summer and fall, when diatom blooms are rarer. *K. brevis* blooms comprise a significant component of the primary production on the west Florida shelf (Vargo et al., 1987) even with relatively low growth rates (doubling ∼0.2 per day; Steidinger et al., 1998). These blooms are often mono-specific with concentrations over 100 cells ml^{-1}, with patches of up to 10,000 cells ml^{-1} (Tester and Steidinger, 1997; Walsh and Steidinger, 2001). The blooms typically contain about 1 μg chlorophyll-a for each 100 cells ml^{-1} (Shanley and Vargo, 1993; Tester et al., 1998), indicating blooms containing from 1 to 100 $\mu g\,l^{-1}$, a major component of the phytoplankton biomass. Thus, it appears likely that *K. brevis* blooms should produce a significant signal in this region during the summer and fall.

Given the late-summer dominance of *K. brevis*, Thomas (2000) and Stumpf (2001) observed that a climatological approach of looking at the chlorophyll anomalies could indicate *K. brevis* blooms. The other dominant bloom-forming organisms during late summer or fall are usually *Trichodesmium* spp. (Lenes et al., 2001). *Trichodesmium* can be distinguished by a unique algorithm (Subramaniam and Carpenter, 1994); it is highly reflective, while *K. brevis* is not (Carder and Steward, 1985).

An anomaly to flag for *K. brevis* is determined as the difference in chlorophyll values between a single image and the mean over 2 months ending 2 weeks prior to the image. For example, an anomaly flag image for September 30 would be found by the difference of the September 30 image and the mean of images collected from July 15 to September 15. The 2-week lag reduces the likelihood that a persistent and stationary bloom will bias the mean. The 2-month period was chosen because it is long enough to have sufficient images to describe the seasonal pattern, but short enough to present a single seasonal pattern. A chlorophyll anomaly of $>1\ \mu g\,l^{-1}$ is considered to be indicative of *K. brevis*. This corresponds to a potential bloom of 100 cells ml^{-1}, the minimum detection of *K. brevis* is considered to be about 50 cells ml^{-1} (Tester et al., 1998).

An examination of imagery and observations of cell counts >100 cells ml^{-1} indicates that chlorophyll anomaly flags accurately identify *K. brevis* bloom and non-bloom events along the west Florida coast 75% of the time, from 1999 to 2001. False positives were more often observed in the spring and early summer before the beginning of the *K. brevis* bloom season in August of all 3 years. As expected, false positives occurred in the Big Bend and Florida Bay areas, which are rarely zones of bloom initiation.

2.3. *K. brevis* and chlorophyll sampling

Datasets for the presence and concentration of *K. brevis* cells were gathered from a variety of sources including the Florida Marine Research Institute (FMRI), Mote Marine Laboratory, and individual researchers including data collected as part of the Ecology and Oceanography of Harmful Algal Blooms (ECOHAB: Florida) program. Cell count information from state-supported monitoring efforts was obtained as available, typically 2–7 days after a sample was collected.

Samples for chlorophyll concentrations and phytoplankton identification and enumeration were collected using a rosette sampler or a bucket. Only samples from the surface layer (depths less than 1.5 m) are presented here. Chlorophyll concentrations were measured fluorometrically (Parsons et al., 1984) as part of the ECOHAB project. Samples for cell counts that could not arrive at a counting lab within 24 h of collection were preserved with Lugol's fixative (Sournia, 1978). Enumeration of cells was conducted as described in Steidinger and Melton-Penta (1999).

2.4. Meteorological information

Meteorological information, particularly wind speed and direction, for the bulletins is obtained from the NOAA Coastal Meteorological Automated Network (CMAN) operated by the NOAA National Data Buoy Center (NDBC), which has stations about every 200 km around the Gulf of Mexico. Stations at Venice and Cape San Blas (in the Florida Panhandle) were used most often. Ten-minute observations are used to determine along-shore and offshore wind vectors. Marine zone weather forecasts are obtained from National Weather Services Tampa Bay office.

3. Results and applications

3.1. Monitoring of blooms

The simplest means of detecting existing blooms (type 1 monitoring) uses chlorophyll as a surrogate for *K. brevis* with a relationship of 1 μg l^{-1} to 100 cells ml^{-1} (or μg chl-a/10^5 cells) as shown in the lab (Shanley and Vargo, 1993; Tester et al., 1998; Tester and Steidinger, 1997). This relationship appears valid in the field when *K. brevis* dominates phytoplankton species composition, until the concentrations become extremely high (Fig. 2). At high cell concentrations, >1000 cells ml^{-1}, chlorophyll may underestimate the amount of *K. brevis*, however this is typically above the level observed to cause all adverse effects in humans, fish, and marine mammals (Tester and Steidinger, 1997).

The relationship between chlorophyll and cell concentration can vary if *K. brevis* is not a consistent proportion of the phytoplankton species composition. In the example shown in Fig. 2, and in Tester et al. (1998), the field chlorophyll concentration remained equal to or less than the expected relationship. This indicates that *K. brevis* dominates the chlorophyll biomass, otherwise the chlorophyll would be greater than expected from the *K. brevis* cell counts (and points would fall above and to the left of the dotted line in Fig. 2). Some variability in the relationship is expected because of

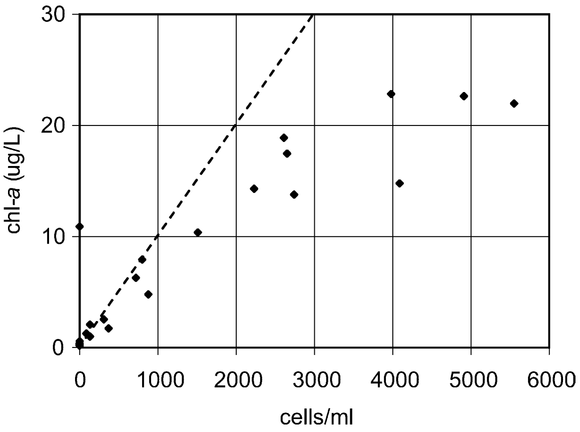


Fig. 2. Relationship of measured chlorophyll-a to *K. brevis* cell concentrations off southwest Florida, September 2001. Dotted line shows the relationship of 1 μg l^{-1} to 100 cells ml^{-1}.

changes in the packaging of chlorophyll in each cell, which causes a variation in the amount of chlorophyll in each cell. Chlorophyll packaging may vary with light intensity, temperature and nutrient availability (Millie et al., 1995; Carder et al., 1999).

Interpretation of chlorophyll imagery requires an understanding of phytoplankton ecology and succession in the area. In areas that commonly have low chlorophyll ($<0.3\,\mu g\,l^{-1}$) such as the northwest Florida shelf and the mid-shelf of the southwest Florida coast, concentrations of chlorophyll alone can be effective at delineating the offshore extent of the HABs. Using chlorophyll alone for analysis of near-shore areas with higher chlorophyll requires access to field data and interpretation by an analyst with an understanding of the chlorophyll and optical patterns in the region.

3.2. Detection of blooms

The need to detect *K. brevis* blooms (type 2) requires additional capability than simply identifying chlorophyll patterns. The chlorophyll anomaly images have provided a means of improving the detection and delineation of these blooms. The anomaly images specifically identify areas that have had an increase in chlorophyll concentration, indicating a new bloom. This information combined with local expertise and biological and physical oceanographic knowledge of the area can guide monitoring efforts to investigate suspect blooms.

The first case of using the bloom detection algorithm occurred in January 2000. In late 1999, a bloom developed along the southwest Florida coast and persisted in the Naples area. Early in January 2000, a fish kill was reported in the Florida Keys suggesting that the bloom may have spread to that area, but state managers lacked specific information to direct sampling efforts. Analysis of the chlorophyll and anomaly images identified an area about 50 km northwest of Key West that indicated the presence of *K. brevis* at concentrations exceeding 500 cells ml^{-1} (Fig. 3A). Sampling efforts focused on that region, with field samples subsequently confirming a bloom with at least 400–600 cells ml^{-1} (medium concentration). The state and federal agencies followed the bloom until it dissipated in the Florida Straits about 2 weeks later.

As a second example, during the first week in October 2000, a *K. brevis* bloom developed along the coast around Tampa Bay and Sarasota. Chlorophyll anomaly images during that time indicated that these areas were *K. brevis* blooms. Further to the south near Sanibel, a new bloom developed and was identified as *K. brevis* through the anomaly imagery. Notice was given to the state, and sampling from Sanibel to Naples area began on October 17, the first systematic sampling to take place south of Sanibel. Cell counts of more than 70 cells ml^{-1} were reported within a few miles of the coast (Fig. 3B). From October 17 to 18 the maximum surface chlorophyll values, at 20–30 km offshore, decreased from 20 to $3\,\mu g\,l^{-1}$ (equivalent of 2000 cells ml^{-1} to <300 cells ml^{-1}). The decrease indicated that the bloom submerged, either swimming or sinking to the bottom. Local fishers reported fish kills through the end of October.

In a third example in 2001, blooms were identified by satellite and field measurement at the same time. In mid-August, a bloom developed off Sanibel but remained south of Sarasota through August 30 (Fig. 4) owing to northerly winds. On September 3, reports began of respiratory distress and fish kills at Sarasota. Imagery processed and delivered on September 4 showed a chlorophyll anomaly near Sarasota, indicating that the bloom had extended north to Sarasota (Fig. 4). Field data collected on September 4–5 verified the bloom in the area. Additional data from Tampa Bay indicated that the bloom had not reached that far north, consistent with the imagery.

After the passage of Tropical Storm Gabrielle on September 14, 2001, the anomaly image indicated that the bloom of *K. brevis* had expanded significantly to encompass areas north of Tampa Bay (Fig. 4). Some increase in chlorophyll evident in the anomaly may have resulted from resuspension of benthic phytoplankton. State and ECOHAB cruises confirmed that the HAB had extended northward (Fig. 5). In addition, the observed *K. brevis* well offshore near 83.2°W, 26.5°N (Fig. 5) appeared partially flagged on September 19 and 22 (at lower left and partially cloud-obscured on September 19 in Fig. 4). While the single image does not support identification of the offshore bloom, examination of previous imagery shows that this feature had moved offshore from the HAB zone.

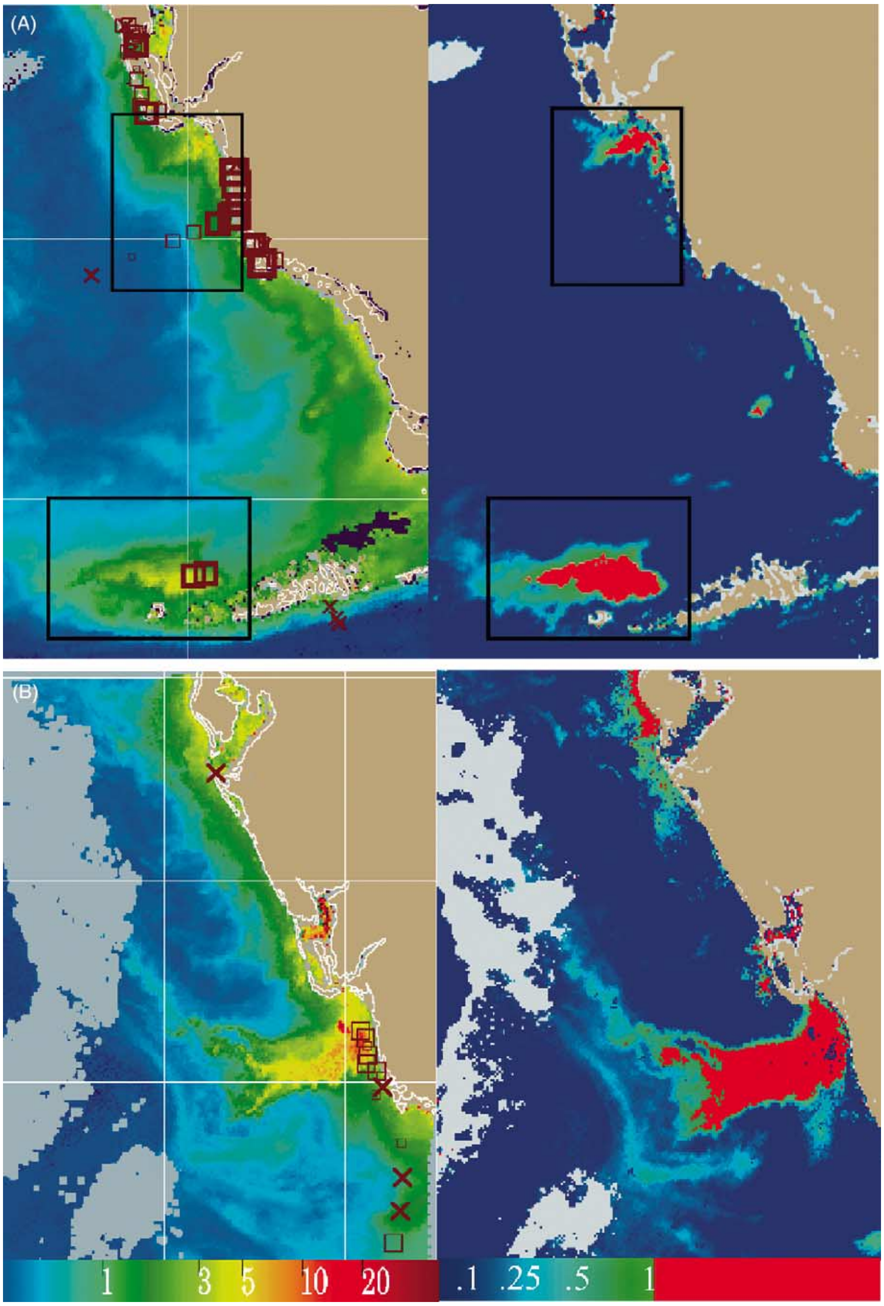


Fig. 3. HAB detection with anomalies for southwest Florida: (A) January 18, 2000 and (B) October 17, 2001. Left images shows SeaWiFS chlorophyll concentration ($\mu g\,l^{-1}$) with symbols showing cell counts taken within 3 days of the image. X means not present, the four sizes of boxes from smallest to largest show present (<10 cells ml^{-1}); low (10–100 cells ml^{-1}); medium (100–1000 cells ml^{-1}); high (>1000 cells ml^{-1}). Right image is the chlorophyll anomaly with red marking anomalies $>1\,\mu g\,l^{-1}$ that would indicate a probable *K. brevis* bloom. Black boxes on January images (A) surround areas of anomalous chlorophyll, and known blooms. A bloom in the region above the upper box (showing measurable cells but no flag) had been flagged in previous weeks but had been static sufficiently long to no longer appear as an anomaly.

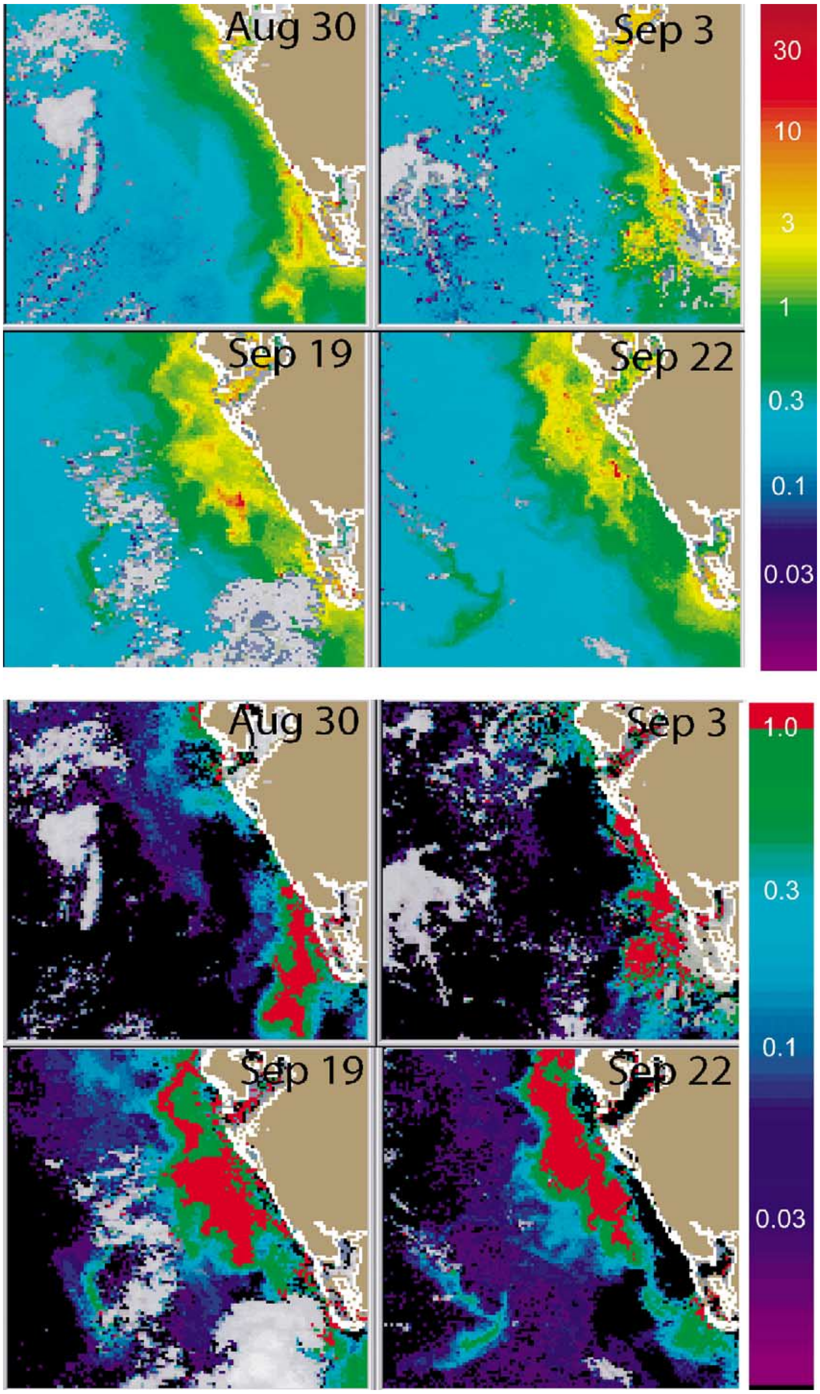


Fig. 4. Chlorophyll (upper group) and anomalies (lower group) showing the sequence of events from August 30 to September 22, 2001 on the Florida coast from Tampa to Sanibel, as well as the comparison between chlorophyll patterns and *K. brevis* anomaly patterns. In the chlorophyll anomaly images, red indicates probable bloom, green adjacent to red is likely low concentration bloom, green in other areas does not usually indicate a bloom (except for feature in lower right of September 22, see text and Fig. 5).

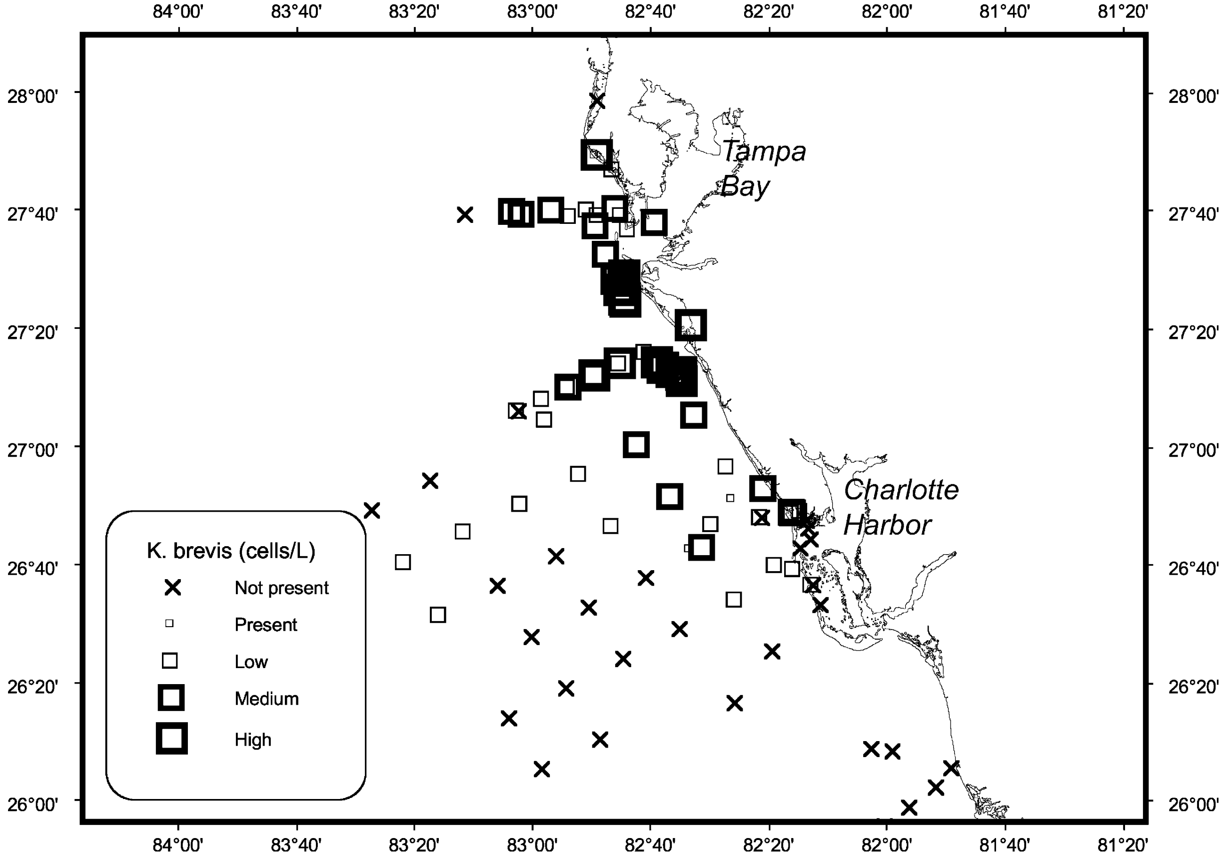


Fig. 5. Cell counts during cruise, September 19–26, 2001; compare to lower images in Fig. 4. Symbols denote blooms (same terminology as Fig. 3).

These and other *K. brevis* blooms were monitored using the anomaly fields starting in late 2000. However, two false alerts (July 2001; August 2002) have been made for diatom blooms occurring near Naples and Sanibel. Once these blooms were identified as diatoms they were tracked appropriately.

3.3. Transport

Determining transport of a bloom (type 3) is needed not only for forecasting future locations of blooms, but also for projecting the current location. Typically, cloud cover and view angle limit the usable satellite images to one or two per week. Field data collection for verification also has constraints on timeliness: sampling (which requires specific materials and access), shipping, and laboratory analysis can together take a week or more. With commercial and recreational shellfish habitat and public access beaches covering an extensive coastline, methods to predict transport of HABs along the coast are essential.

Based on the assumption that these *K. brevis* blooms are maintained within the surface layers near the coast, a rudimentary analyses of bloom transport (type 3) is possible using surface wind data. Tester et al. (1991) used estimated wind drift to show transport of *K. brevis* along the coasts of North and South Carolina. Using the same analysis procedure for winds, Culver et al. (2000) have shown that the blooms travel westward along the northern Gulf coast (Florida Panhandle, Alabama, Mississippi) at about 7% of the along-shore wind speed. The westward transport of the bloom is consistent with prevailing coastal currents during this time of year. With the general north–south orientation of the southwest Florida coastline, southerly winds favor northward transport at the coast, and northerly winds should favor southerly transport.

In 2001, prediction of HAB transport was first provided to Florida resource managers. Until August 30, northerly winds of 1–3 m s^{-1} prevailed, leading to the movement of the bloom south and offshore of Sanibel. A reversal of winds occurred on August 30. The southerly winds of 1–3 m s^{-1} between August 30 and September 3 led to northward transport of a bloom from Sanibel region about 50 km towards Sarasota (Fig. 4). When Tropical Storm Gabrielle passed through southwest Florida, she generated strong southerly winds prior to landfall near Venice. Afterwards, the bloom extended northward from Sarasota to north of Tampa Bay. On the northwest coast, the 2001 bloom was estimated to move west along the entire Florida Panhandle to near the Alabama border. Cells were found in far western Florida and coastal Alabama at the predicted time, although at very low concentrations (3 cells ml^{-1}).

3.4. *Prediction of landfall*

The ultimate goal of forecasting is prediction of landfall (type 4) so that management agencies can anticipate sampling. Satellite imagery was considered ideal for this purpose. As *K. brevis* has been considered positively phototactic (Heil, 1986) and CZCS imagery from 1978 showed an extraordinarily large bloom (see Steidinger and Haddad, 1981), it has generally been thought that satellite remote sensing would detect blooms offshore as they developed, allowing for prediction of landfall. However, in northwest Florida in August 1999 and September 2000, and southwest Florida in September 2000, fully developed blooms appeared at the coast with no evidence of offshore presence in the satellite imagery. The satellite can detect features to one optical depth (the inverse of the diffuse attenuation coefficient), which is less than 10 m on the Florida shelf. Thus, a bloom within the upper 5–10 m of water should appear as a patch of elevated chlorophyll concentration, so that it should be visible in the satellite imagery. Millie et al. (1995), however, reported that *K. brevis* cannot be grown in the lab at greater than 220 μE m^{-2} s^{-1}, which is much less than the maximum light available at the ocean surface at noon (1000–2000 μE m^{-2} s^{-1}). The implication of the light preferences and the satellite observations is that the blooms begin at depth on the shelf.

Stumpf et al. (1998) showed a correlation of *K. brevis* occurrence at the west coast of Florida with upwelling-favorable winds (Fig. 6). The blooms usually start in late summer (cf. Tester and Steidinger, 1997) when a season of upwelling-favorable winds begins, and dissipate in winter as the upwelling season ends. This association of blooms and winds is consistent with the development of *K. brevis* blooms at depth and subsequent transport to the shore by onshore bottom flow (Li and Weisberg, 1999) produced by upwelling-favorable winds. This hypothesis provides a basis for predicting the initial appearance of a bloom at the coast, and the likelihood of re-intensification of a bloom.

Several conditions must be met to predict landfall using this hypothesis.

1. A HAB must be present offshore (see Tester and Steidinger, 1997; Walsh and Steidinger, 2001, for theories on offshore initiation).

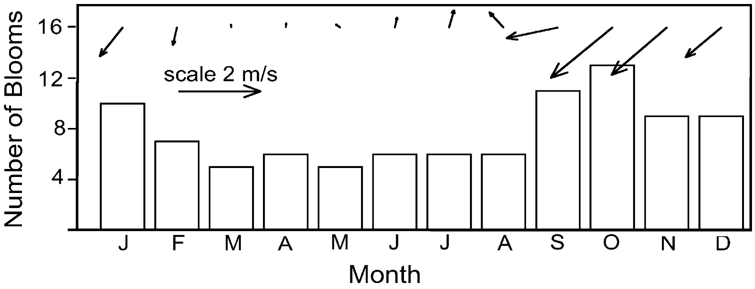


Fig. 6. The frequency of *K. brevis* blooms from Tampa to Naples (bars) compared with the monthly mean wind direction (arrows showing direction toward which winds is blowing) at Tampa, FL, from 1960 to 1998 (after Stumpf et al., 1998).

2. The bloom must have developed without dispersal, so winds should have been mild prior to the upwelling event; particularly no strong downwelling winds.
3. Upwelling-favorable winds must occur after a bloom has developed offshore, for southwest Florida, these winds would be easterly to northeasterly.

In September 2000, these conditions were met. Cell counts of up to 70 ml^{-1} were detected 20 km offshore of Sarasota in early September. Winds had been generally calm, and the forecast at the end of September called for north to northeasterly winds at 15 knots (7.7 $\mathrm{m\,s}^{-1}$). This led to an advisory on September 26 for the state of Florida to watch for a bloom at the coast within the first days of October. By October 4, cell counts of up to 700 ml^{-1} were measured from Venice to Tampa Bay. In 2001, similar conditions applied prior to the first HAB at the coast. Significantly, two major intensifications of the bloom occurred in 2001, each during upwelling-favorable winds.

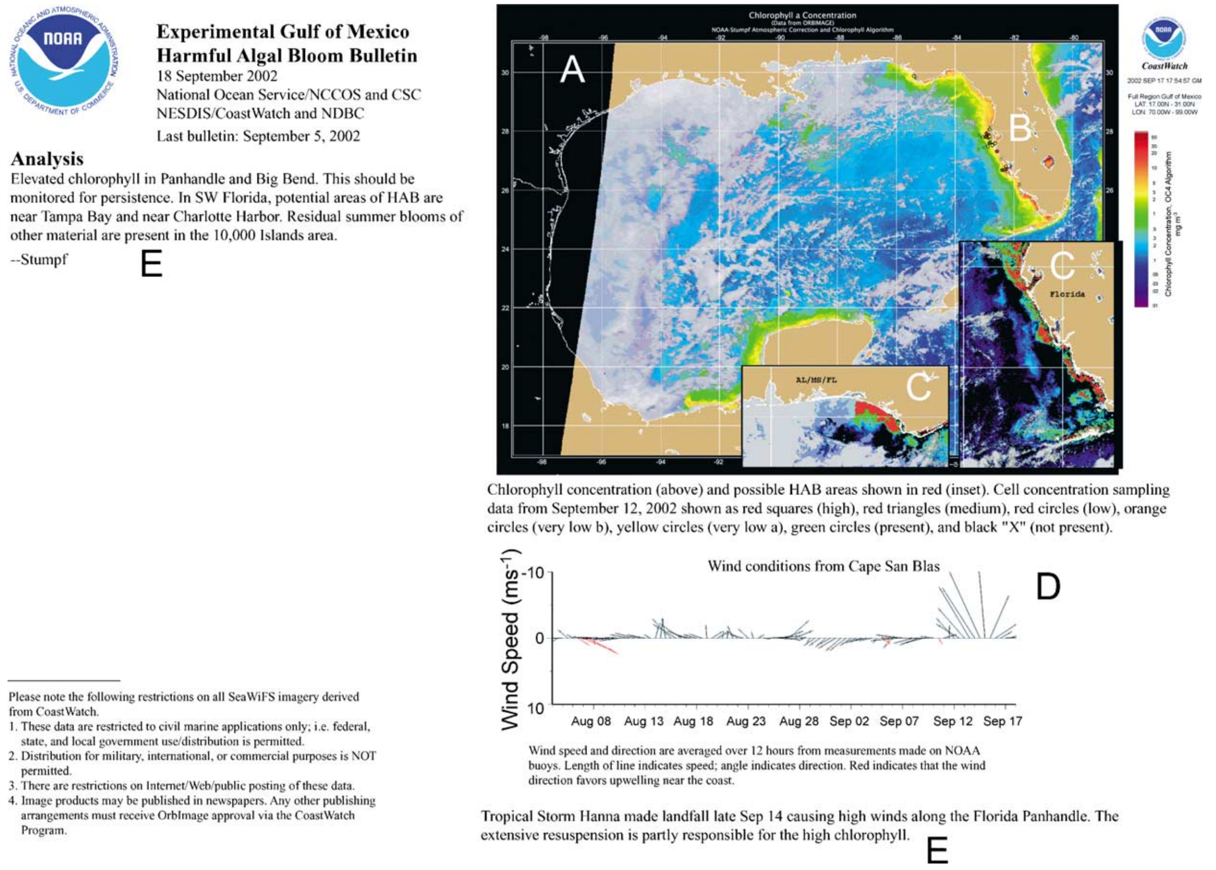
4. Discussion

The use of imagery and winds has had several successes in finding, monitoring, and predicting transport and landfall of *K. brevis* blooms. However, the success of the system depends on the extensive knowledge of the ecology of the species and the oceanographic processes in the area. The use of the climatological anomaly image to identify potential HAB areas is effective because of the habitat requirements of *K. brevis*. The organism inhabits oligotrophic water and low-chlorophyll water of the Florida shelf (Gilbes et al., 1996), prefers higher salinity water for initiation, and generally blooms in the late summer and fall when there is less competition from other phytoplankton species. The other primary bloom-forming organism during late summer on this coast, *Trichodesmium* spp. (Walsh and Steidinger, 2001), can be detected from satellite due to high backscatter (Subramaniam and Carpenter, 1994).

There are areas and times of the year when the use of the anomaly is inappropriate and ineffective at detecting *K. brevis*. The Florida mid-shelf often has a significant spring diatom bloom extending southward from the Panhandle (Gilbes et al., 1996). This bloom may occasionally be identified as a chlorophyll anomaly; but the HABs rarely start in those months. The embayment between Naples and Key West (including Florida Bay) has tannin-rich water, and late-summer non-HAB blooms that may be confused with *K. brevis*. Similarly, the Big Bend of Florida (Fig. 1) receives tannin-rich rivers that drain coastal swamps. Both of these areas rarely have HABs, but the discolored water in the river plumes may falsely indicate a HAB. HAB indications in these areas of highly discolored water should be generally ignored. Similarly, the algorithm would be invalid on the Louisiana and Alabama coasts owing to high river inflow, but it may apply to central and south Texas. The challenge is to correctly identify HABs on the edges of these areas. For example, the area between the Florida Panhandle and Big Bend was flagged for a HAB in October 2001, but the flag was discounted as potentially faulty. However, it was a *K. brevis* bloom and if it had been correctly identified, could have provided some assistance in responding to a rare and costly HAB that entered the coastal bays (Apalachicola Bay) during the peak of oyster-harvest season.

Forecasting transport or prediction requires a better understanding of the behavior of *K. brevis*, as well as the local seasonal circulation patterns. Initiation conditions are still poorly known; questions exist on nutrient sources (Ingle and Martin, 1971; Walsh and Steidinger, 2001); and we lack a reliable means of monitoring the subsurface water column on the shelf. Upwelling-favorable winds are an insufficient condition to predict the occurrence of *K. brevis* blooms. On the southwest Florida coast, the blooms tend to recur each year, so there is a high likelihood of defining the additional conditions that initiate the blooms offshore. *K. brevis* blooms along the northwest Florida coast are less frequent. These blooms may be due to Loop Current intrusions pushing water massses that hold *K. brevis* further north. Also, understanding the demise of *K. brevis* blooms will aid in correctly monitoring them.

Information gained from imagery and other data sources has been provided to federal, state, and local governments in the form of a near real-time bulletin that integrates the information sources and four types of forecasts into a single format (Fig. 7). These bulletins are provided frequently (once or twice a week)



Experimental Gulf of Mexico
Harmful Algal Bloom Bulletin
18 September 2002
National Ocean Service/NCCOS and CSC
NESDIS/CoastWatch and NDBC
Last bulletin: September 5, 2002

Analysis

Elevated chlorophyll in Panhandle and Big Bend. This should be monitored for persistence. In SW Florida, potential areas of HAB are near Tampa Bay and near Charlotte Harbor. Residual summer blooms of other material are present in the 10,000 Islands area.

--Stumpf

Chlorophyll concentration (above) and possible HAB areas shown in red (inset). Cell concentration sampling data from September 12, 2002 shown as red squares (high), red triangles (medium), red circles (low), orange circles (very low b), yellow circles (very low a), green circles (present), and black "X" (not present).

Wind speed and direction are averaged over 12 hours from measurements made on NOAA buoys. Length of line indicates speed; angle indicates direction. Red indicates that the wind direction favors upwelling near the coast.

Tropical Storm Hanna made landfall late Sep 14 causing high winds along the Florida Panhandle. The extensive resuspension is partly responsible for the high chlorophyll.

Please note the following restrictions on all SeaWiFS imagery derived from CoastWatch.

1. These data are restricted to civil marine applications only; i.e. federal, state, and local government use/distribution is permitted.
2. Distribution for military, international, or commercial purposes is NOT permitted.
3. There are restrictions on Internet/Web/public posting of these data.
4. Image products may be published in newspapers. Any other publishing arrangements must receive OrbImage approval via the CoastWatch Program.

Fig. 7. An example bulletin distributed state managers around the Gulf of Mexico. The bulletin includes the chlorophyll image for the Gulf of Mexico (A), with available cell count data superimposed (right of B), one or more anomaly images for an area of particular concern (C), the wind vectors for the preceding 2 weeks (D), and an analysis of the imagery and winds (E).

as portable document format (PDF) files during the initiation of a bloom with updates during significant movements or events. This effort will incorporate more sophisticated products and models, thereby improving the timeliness and reducing the interpretation required by the users. In addition, the algorithms and methods will be examined for applicability to the western Gulf of Mexico. The information provided in the bulletins depends on routine ocean and weather observing systems that are available in the Gulf of Mexico. However, while interpretation of the datasets will probably always require an analyst, improvements in the products and models will simplify the training and expertise required.

The capability to provide synoptic information to the management community has changed the monitoring strategies for *K. brevis* events in Florida. The state uses the information to aid in planning deployments of employees and volunteers. Careful analysis of the products has helped limit inappropriate interpretation, and false alerts have occurred about once per season. The bulletins are distributed to agencies and individuals in all the Gulf states thereby providing some additional information to guide monitoring efforts. The integrated information allows the state to better anticipate HABs and focus their sampling efforts on threatened shellfish-harvesting areas. Advance notice will prepare state and local agencies for the many management responsibilities that accompany HAB events, including cleanup of dead fish and debris from the beaches, providing accurate public advisories to reduce the economic impacts, and protection of marine mammals including endangered manatees. Advance notice will allow more options in managing these events.

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References

Brown, C.W., Yoder, J.A., 1994. Coccolithophorid blooms in the global ocean. J. Geophysical Res. 99 (C4), 7467–7482.

Buskey, E.J., Stewart, S., Peterson, J., Collumb, C., 1996. Current status and historical trends of brown tide and red tide phytoplankton blooms in the Corpus Christi Bay, National Estuary Program study area. Corpus Christi Bay National Estuary Program, CCBNEP-07. Corpus Christi Texas, 85 pp.

Cannizzaro, J.P., Carder, K.L., Chen, F.R., Walsh, J.J., Lee, Z.P., Heil, C., Villareal, T., 2002. A novel optical classification technique for detection of red tides in the Gulf of Mexico: application to the 2001–2002 bloom event. In: Proceedings of the 10th International Conference on Harmful Algae, St. Pete Beach, Florida, 21–25 October 2002. p. 43.

Carder, K., Steward, R.G., 1985. A remote-sensing reflectance model of a red-tide dinoflagellate off west Florida. Limnol. Oceanogr. 30, 286–298.

Carder, K.L., Chen, F.R., Lee, Z.P., Hawes, S.K., 1999. Semianalytic moderate-resolution imaging spectrometer algorithms for chlorophyll-a and absorption with bio-optical domains based on nitrate-depletion temperatures. J. Geophys. Res. 104 (C3), 5403–5421.

Cullen, J.J., Ciotti, A.M., Davis, R.F., Lewis, M.R., 1997. Optical detection and assessment of algal blooms. Limnol. Oceanogr. 42 (5), 1223–1239.

Culver, M.E., Soracco, M., Stumpf, R.P., Change, P.S., Steidinger, K.A., 2000. Integrating wind data to determine the influence on movement of a harmful algal bloom event along the northwest coast of Florida. Proceedings of the 6th International Conference on Remote Sensing for Marine and Coastal Environments. Veridian ERIM Intl., Ann Arbor, MI, USA, pp. 25–27.

Dortch, Q., Moncreiff, C.A., Mendenhall, W., Parsons, M.L., Franks, J.S., Hemphill, K.W., 1998. Spread of *Gymnodinium breve* into the northern Gulf of Mexico. In: Reguera, B., Blanco, J., Fernandez, M.L., Wyatt, T. (Eds.), Harmful Algae. Xunta de Galicia and Intergovernmental Oceanographic Commission of UNESCO, pp. 143–144.

Gilbes, F., Tomas, C., Walsh, J.J., Muller-Karger, F., 1996. An episodic chlorophyll plume on the west Florida shelf. Continent. Shelf Res. 16, 1201–1224.

Gower, J.F.R., 1994. Red tide monitoring using AVHRR HRPT imagery from a local receiver. Remote Sensing Environ. 48, 309–318.

Haddad, K.D., 1982. Hydrographic Factors Associated with West Florida Toxic Red Tide Blooms: An Assessment for Satellite Prediction and Monitoring, M.Sc. Thesis. University of South Florida, St. Petersburg, FL.

Heil, C.A., 1986. Vertical Migration of *Ptychodiscus brevis* (Davis) Steidinger, M.Sc. Thesis. University of South Florida, St. Petersburg, FL, 118 pp.

Ingle, R.M., Martin, D.F., 1971. Prediction of the Florida red tide by means of the iron index: red tide, iron and humic acid levels in streams. Environ. Lett. 1, 69–74.

Lenes, J.M., Darrow, B.P., Cattrall, C., Heil, C.A., Callahan, M., Vargo, G.A., Byrne, R.H., 2001. Iron fertilization and the Trichodesmium response on the west Florida shelf. Limnol. Oceanogr. 46 (6), 1261–1277.

Li, Z., Weisberg, R.H., 1999. West Florida shelf response to upwelling favorable wind forcing: kinematics. J. Geophys. Res. 104 (C6), 13507–13527.

Millie, D.F., Kirkpatrick, G.B., Vinyard, B.T., 1995. Relating photosynthetic pigments and in vivo optical density spectra to irradiance for the Florida red-tide dinoflagellate *Gymnodinium breve*. Mar. Ecol. Prog. Ser. 120, 65–75.

Millie, D.F., Schofield, O.M., Kirkpatrick, G.B., Johnsen, G., Tester, P.A., Vinyard, B.T., 1997. Detection of harmful algal blooms using photopigments and absorption signatures: a case study of the Florida red-tide dinoflagellate, *Gymnodinium breve*. Limnol. Oceanogr. 42 (5), 1240–1251.

Mueller, J.L., 1979. Prospects for measuring phytoplankton bloom extent and patchiness using remotely sensed ocean color images: an example. In: Taylor, D.L., Seliger, H.H. (Eds.), Toxic Dinoflagellate Blooms. Elsevier, New York, pp. 303–308.

Parsons, T.R., Maita, Y., Lalli, C.M., 1984. A Manual of Chemical and Biological Methods for Seawater Analysis. Pergamon Press, New York, 173 pp.

Schofield, O., Grzymski, J., Bissett, W.P., Kirkpatrick, G.J., Millie, D.F., Moline, M., Roesler, C., 1999. Optical monitoring and forecasting systems for harmful algal blooms: possibility or pipe dream? J. Phycol. 35, 1477–1496.

Shanley, E., Vargo, G.A., 1993. Cellular composition, growth, photosynthesis, and respiration rates of *Gymnodinium breve* under varying light levels. In: Smayda, T.J., Shimizu, Y. (Eds.), Toxic Phytoplankton Blooms in the Sea. Elsevier, New York, pp. 919–923.

Sournia, A., 1978. Phytoplankton manual. Monographs on Oceanographic Methodology, vol. 6. UNESCO, Paris, 337 pp.

Steidinger, K.A., Haddad, K.D., 1981. Biologic and hydrographic aspects of red tides. Bioscience 31, 814–819.

Steidinger, K.A., Melton-Penta, H.L., 1999. Harmful microalgae and associated public health risks in the Gulf of Mexico. US EPA Grants #MX004729-95-0. Florida Marine Research Institute, St. Petersburg, FL, 63 pp.

Steidinger, K.A., Vargo, G.A., Tester, P.A., Tomas, C.R., 1998. Bloom dynamics and physiology of *Gymnodinium breve* with emphasis on the Gulf of Mexico. In: Anderson, D.M., Cambella, A.D., Hallegraeff, G.M. (Eds.), Physiological Ecology of Harmful Algal Blooms. Springer, New York, pp. 135–153.

Stumpf, R.P., 2001. Applications of satellite ocean color sensors for monitoring and predicting harmful algal blooms. J. Hum. Ecol. Risk Assess. 7, 1363–1368.

Stumpf, R.P., Tyler, M.A., 1988. Satellite detection of bloom and pigment distributions in estuaries. Remote Sensing Environ. 24, 385–404.

Stumpf, R.P., Ransibrahmanakul, V., Steidinger, K.A., et al. 1998. Observations of sea surface temperature and winds in association with Florida, USA red tides (*Gymnodinium breve* blooms). In: Reguera, B., Blanco, J., Fernandez, M.L., Wyatt, T. (Eds.), Harmful Algae. Xunta de Galicia and Intergovernmental Oceanographic Commission of UNESCO, Paris, France, pp. 145–148.

Stumpf, R.P., Arnone, R.A., Gould, R.W., Martinolich, P., Ransibrahmanakul, V., Tester, P.A., Steward, R.G., Subramaniam, A., Culver, M.E., Pennock, J.R., 2000. SeaWiFS ocean color data for US Southeast coastal waters. Proceedings of the Sixth International Conference on Remote Sensing for Marine and Coastal Environments. Veridian ERIM Intl., Ann Arbor, MI, USA, pp. 25–27.

Subramaniam, A., Carpenter, E.J., 1994. An empirically derived protocol for the detection of blooms of the marine cyanobacterium *Trichodesmium* using CZCS imagery. Int. J. Remote Sensing 15 (8), 1559–1569.

Tester, P.A., Steidinger, K.A., 1997. *Gymnodinium breve* red tide blooms: initiation, transport, and consequences of surface circulation. Limnol. Oceanogr. 42 (5), 1039–1051.

Tester, P.A., Stumpf, R.P., 1998. Phytoplankton blooms and remote sensing: what is the potential for early warning. J. Shellfish Res. 17 (5), 1469–1471.

Tester, P.A., Stumpf, R.P., Vukovich, F.M., Fowler, P.K., Turner, J.T., 1991. An expatriate red tide bloom: transport, distribution, and persistence. Limnol. Oceanogr. 36 (5), 1053–1061.

Tester, P.A., Stumpf, R.P., Steidinger, K.A., 1998. Ocean color imagery: what is the minimum detection level for *Gymnodinium breve* blooms? In: Reguera, B., Blanco, J., Fernandez, M.L., Wyatt, T. (Eds.), Harmful Algae. Xunta de Galicia and Intergovernmental Oceanographic Commission of UNESCO, Paris, France, pp. 149–151.

Thomas, D.G., 2000. The Use of SeaWiFS-Derived Bio-Optical Properties to Characterize Harmful Algal Blooms, M.Sc. Thesis. University of Southern Mississippi, Mississippi.

Vargo, G.A., Carder, K.L., Gregg, W., Shanley, E., Heil, C., Steidinger, K.A., Haddad, K.D., 1987. The potential contribution of primary production by red tides to the west Florida shelf ecosystem. Limnol. Oceanogr. 32, 762–767.

Walsh, J.J., Steidinger, K.A., 2001. Saharan dust and Florida red tides: the cyanophyte connection. J. Geophys. Res. 106 (c6), 11597–11612.