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Red tide detection and tracing using MODIS fluorescence data: A regional example in SW Florida coastal waters

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Abstract

Near real-time data from the MODIS satellite sensor was used to detect and trace a harmful algal bloom (HAB), or red tide, in SW Florida coastal waters from October to December 2004. MODIS fluorescence line height (FLH in W m^{-2} μm^{-1} sr^{-1}) data showed the highest correlation with near-concurrent in situ chlorophyll-*a* concentration (Chl in mg m^{-3}). For Chl ranging between 0.4 to 4 mg m^{-3} the ratio between MODIS FLH and in situ Chl is about 0.1 W m^{-2} μm^{-1} sr^{-1} per mg m^{-3} chlorophyll (Chl = 1.255 $(FLH \times 10)^{0.86}$, r = 0.92, n = 77). In contrast, the band-ratio chlorophyll product of either MODIS or SeaWiFS in this complex coastal environment provided false information. Errors in the satellite Chl data can be both negative and positive (3 – 15 times higher than in situ Chl) and these data are often inconsistent either spatially or temporally, due to interferences of other water constituents. The red tide that formed from November to December 2004 off SW Florida was revealed by MODIS FLH imagery, and was confirmed by field sampling to contain medium (10^4 to 10^5 cells L^{-1}) to high ($>10^5$ cells L^{-1}) concentrations of the toxic dinoflagellate *Karenia brevis*. The FLH imagery also showed that the bloom started in mid-October south of Charlotte Harbor, and that it developed and moved to the south and southwest in the subsequent weeks. Despite some artifacts in the data and uncertainty caused by factors such as unknown fluorescence efficiency, our results show that the MODIS FLH data provide an unprecedented tool for research and managers to study and monitor algal blooms in coastal environments.

Keywords: Harmful Algal Bloom; Red tide; *Karenia brevis*; Ocean color; Remote sensing; MODIS; SeaWiFS; Chlorophyll; CDOM; Fluorescence line height; Water-leaving radiance

1. Introduction

Harmful Algal Blooms (HABs) occur every year on the west Florida shelf (WFS), mainly between late fall and early spring but also occasionally at other times of the year. Although many phytoplankton blooms are not toxic, these HABs on the WFS are primarily caused by the toxic species *Karenia brevis* (previously known as *Gymnodinium breve* or *G. breve*). *K. brevis* can produce brevetoxins that accumulate in shellfish (e.g., oyster and clam) and cause mortalities of fish, bird, and marine mammals, and can irritate the eye and respiratory systems of animals including humans. Indeed, *K. brevis* blooms represent a serious hazard to human populations and affect economic growth in the Gulf of Mexico (Anderson, 1995). *K. brevis* blooms off Florida can turn water to look red, brown, or even black, and they are typically referred to as “red tides.”

There have been extensive red tide sampling efforts to document the WFS HAB origin, fate, duration, frequency, and distribution (Anderson, 1995; Morton & Burklew, 1969; Steidinger & Haddad, 1981; Steidinger & Ingles, 1972; Steidinger & Joyce, 1973; Steidinger et al., 1998; Walsh & Steidinger, 2001; Williams & Ingles, 1972). However, to date the exact mechanisms causing *K. brevis* blooms remain unclear. Historical data have been interpreted

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to suggest that red tide typically initiates offshore in nutrient-poor waters (Tester & Steidinger, 1997) and then moves toward shore under favorable winds and currents, where growth may be stimulated by additional nutrients from coastal runoff, or where accumulation may occur due to convergence of waters along fronts. Several hypotheses have been proposed (e.g., Walsh & Steidinger, 2001), yet testing of these hypotheses has been a challenging task and no conclusive mechanism for HAB formation has been identified.

Timely detection and observation of HABs is critical for hypothesis testing, environmental assessment, ecological modeling, and for prediction and mitigation of red tide impacts. Significant efforts have been dedicated to environmental monitoring, most of which relies on field measurements and taxonomy to differentiate between various species and to determine each individual concentration. Sample collection and analysis are limited in both space and temporal frequency. There is some evidence that various HAB species may have distinguishable optical properties (e.g., Cullen et al., 1997; Kahru & Mitchell, 1998; Kirkpatrick et al., 2000; Lohrenz et al., 1999; Millie et al., 1997 also see Schofield et al., 1999 for review), but these methods still require more research.

Current satellite ocean color sensors provide synoptic coverage of the coastal ocean at near daily frequencies or better. Multiple observations per day are possible using the Sea-viewing Wide Field-of-view Sensor (SeaWiFS, McClain et al., 1998) and the two Moderate Resolution Imaging Spectroradiometer sensors (MODIS, Esaias et al., 1998; Terra for morning passes and Aqua for afternoon passes). These sensors provide a unique testbed for the future National Polar-Orbiting Operational Environmental Satellite System (NPOESS) and the NPOESS Preparatory Mission (NPP), which will carry the Visible/Infrared Imager/Radiometer Suite (VIIRS) instruments that are similar in capability to SeaWiFS and MODIS. It is important to understand whether these sensors provide a useful HAB monitoring capability.

The color of the ocean, i.e., the spectral water-leaving radiance, $L_w(\lambda)$, is the combined result of the properties of various colored constituents in the surface ocean, namely water molecules, phytoplankton, detritus, colored dissolved organic matter (CDOM), suspended sediments, and bottom reflectance (if the water is optically shallow). Chlorophyll per cell for *K. brevis* ranges from approximately ~8.5 pg for natural populations to ~25 pg for cultures (Evens et al., 2001). Assuming 10 pg/cell, concentrations of 10^4 cells L^{-1} would contain ~0.1 mg m^{-3} of chlorophyll, close to the background chlorophyll levels in the open Gulf of Mexico. To be detectable by a sensitive satellite sensor, cell concentrations need to be $\sim 5 \times 10^4$ to 10^5 cell L^{-1} (~0.5 to 1 mg m^{-3} chlorophyll). At these concentrations *K. brevis* may cause fish kills (Steidinger et al., 1998).

Stumpf et al. (2003a) proposed to use satellite-derived chlorophyll concentration (Chl) anomalies as indices of potential HABs. This method was implemented by NOAA's CoastWatch program for HAB monitoring off Florida with some success (Tomlinson et al., 2004). However, the method has two major difficulties: 1) the satellite chlorophyll concentrations suffer from uncertainties in the atmospheric correction and interference of other colored compounds and/or shallow bottom; 2) it is difficult to determine whether high chlorophylls are due to non-toxic species or to a HAB.

These difficulties cannot be overcome with traditional bio-optical algorithms. New algorithms have been proposed based on in situ data to use the backscattering/Chl ratio or the fluorescence/Chl ratio to differentiate HABs from other blooms (Cannizzaro et al., accepted), but operational application of these new algorithms using satellite data still requires significant research (e.g., Hu et al., submitted for publication).

The MODIS sensors are equipped with several bands that are specifically designed to measure the solar-stimulated fluorescence of phytoplankton living in surface waters. Pioneering studies in the 1970's and 1980's using airborne sensors and in situ surveys showed a linear correlation between chlorophyll concentration and natural fluorescence (e.g., Fischer & Kronfeld, 1990; Gower & Borstad, 1981; Hoge et al., 1986; Letelier & Abott, 1996; Neville & Gower, 1977; MODIS Algorithm Theoretical Basis Document; others). Briefly, MODIS Bands 13, 14, and 15 (centered at 665.1, 676.7, and 746.3 nm, respectively, with 10 nm bandwidth) are used to estimate the FLH. A baseline is first formed between radiances for Bands 13 and 15, and then subtracted from Band 14 radiance to obtain the FLH. Because of the use of a linear baseline, FLH values in clear waters, where Chl is ~0.1–0.2 mg m^{-3}, are often negative (Letelier & Abott, 1996).

MODIS/Terra and MODIS/Aqua were launched in December 1999 and May 2002, respectively. To date, studies using the MODIS FLH data have focused on comparing the MODIS/Terra FLH and aircraft fluorescence data (Hoge et al., 2003), and on comparing MODIS/Terra FLH data and SeaWiFS Chl data (Gower & Borstad, 2004). A study of coastal runoff by Hu et al. (2004) used MODIS FLH to distinguish a phytoplankton bloom from a coastal dark water patch caused by riverine discharge. The MODIS FLH data have not been used more extensively to study oceanographic phenomena, and certainly not to address operational requirements such as observation of HABs.

In this paper, we present first results of application of the MODIS FLH data for detection and tracing of HABs. We focus on a red tide event in coastal waters of SW Florida to demonstrate the application. Our objectives are to 1) assess the reliability of the MODIS FLH data relative to standard satellite-derived chlorophyll products, and 2) assess whether the MODIS FLH data can be used effectively to detect and monitor HABs.

2. Data and methods

2.1. In situ data

Two surveys were conducted as a joint effort between the University of Miami and NOAA/AOML by the R/V Walton Smith in coastal waters off SW Florida, the first from 14 to 23 October 2004 and the second from 8 to 17 December 2004. These surveys collected along-track (flow-through, with water pumped from about 1-m depth) hydrographic and bio-optical data. The temperature and salinity data was collected using a Seabird model 21 thermosalinograph, and the in vivo chlorophyll fluorescence was measured by a Seapoint chlorophyll fluorometer. At discrete stations, water samples were collected for quantitative analysis of Chl to calibrate the underway fluorescence measurements. Samples were filtered through GF/F filters, and pigments were extracted using a 60/40 mixture of Acetone and Dimethyl Sulfoxide (Shoaf & Lium, 1976), and then measured using a Turner Designs model TD-700 fluorometer.

Cell counts of *K. brevis* were obtained from the Florida Fish and Wildlife Research Institute (FWRI). The data were collected by FWRI, local agencies, volunteers, Mote Marine Laboratory, and University of South Florida researchers. The data were largely limited to observations within a few kilometers of the shoreline. Some of the FWRI samples were counted live, some using the Utermohl method with a light microscope that was sometimes inverted, and some samples were preserved in Lugol iodine solution for subsequent counting. Occasional samples from slightly deeper coastal waters were collected through the MERHAB program coordinated by FWRI.

2.2. Satellite data

SeaWiFS data were captured and processed at the University of South Florida (USF) with up-to-date algorithms and software (NASA SeaDAS4.6). An iterative approach (Arnone et al., 1998; Stumpf et al., 2003b) for sediment-rich waters, based on the Gordon and Wang (1994) algorithm, was used to correct for the atmospheric interference in the six ocean color bands in turbid coastal waters to obtain $L_w(\lambda)$, which were then used in the OC4 band-ratio algorithm (O'Reilly et al., 2000) to estimate Chl in mg m^{-3}.

MODIS data were also captured and processed at USF using similar algorithms. A baseline subtraction algorithm (Letelier & Abott, 1996) was used to estimate FLH, and a band-ratio algorithm (OC3M; O'Reilly et al., 2000) was used to estimate Chl.

Water-leaving radiance data in the three visible MODIS bands (551, 488, and 443 nm) were used to derive composite, enhanced RGB (ERGB) images. This type of image carries information from three MODIS bands, and therefore allows for detection of more spatial features than the Chl imagery, which was derived from only two bands per pixel.

2.3. Validation

Rigorously, satellite data validation should be performed with in situ data collected within ±2–3 h of the satellite overpass (Bailey et al., 2000). In practice, however, due to frequent cloud cover or other inconveniences, this often leads to very few matching data pairs. In this study, except for a short nearshore segment (within 10 m water depth) we relaxed the window to 6 h, primarily for validation of the observed cross-shelf synoptic features in FLH and Chl.

To reduce errors from satellite sensor digitization/noise, a median value from a 3×3 box was used to filter the image data (Hu et al., 2001). Similarly, for each satellite pixel (about 1×1 km^2), a median value from the multiple in situ data points was used.

3. Results

3.1. Comparison between satellite and in situ data

Flow-through chlorophyll fluorescence was converted to Chl using discrete water samples. Although some variation in chlorophyll fluorescence efficiency may exist because samples were collected during daytime, nighttime, and from different water types (coastal, fresh water to open ocean water) where phytoplankton species may be different, high correlation coefficients (~0.94, $n > 80$) for both the October and December 2004 cruises were obtained, and the relationships do not significantly deviate from the 1:1 line. The uncertainty was ~10–20%. The converted Chl data were used to compare with the satellite estimates.

Fig. 1 shows several MODIS/Aqua images and nearly concurrent ship tracks. The images showed large differences in the spatial distributions of detected features. The ERGB images (Fig. 1c and f) differentiated dark features, caused by high absorption of light due to chlorophyll and/or CDOM, from bright features caused by either sediment resuspension (brown to white) or shallow bottom (cyan to white). The FLH image (Fig. 1a) showed detailed patchiness within the dark feature observed in the ERGB image off Charlotte Harbor. In contrast, the Chl images suggested that a continuous, broad region of high concentration was present along the entire southwestern coast of Florida. The Chl images also masked any contrast between dark and bright water features because all color changes are interpreted by the band-ratio algorithm as changes in "chlorophyll concentration".

On 19 October 2004, the MODIS data were collected within ±2 h of the ship observations along the nearshore transect off Charlotte Harbor (Fig. 1a and b). Fig. 2 shows in

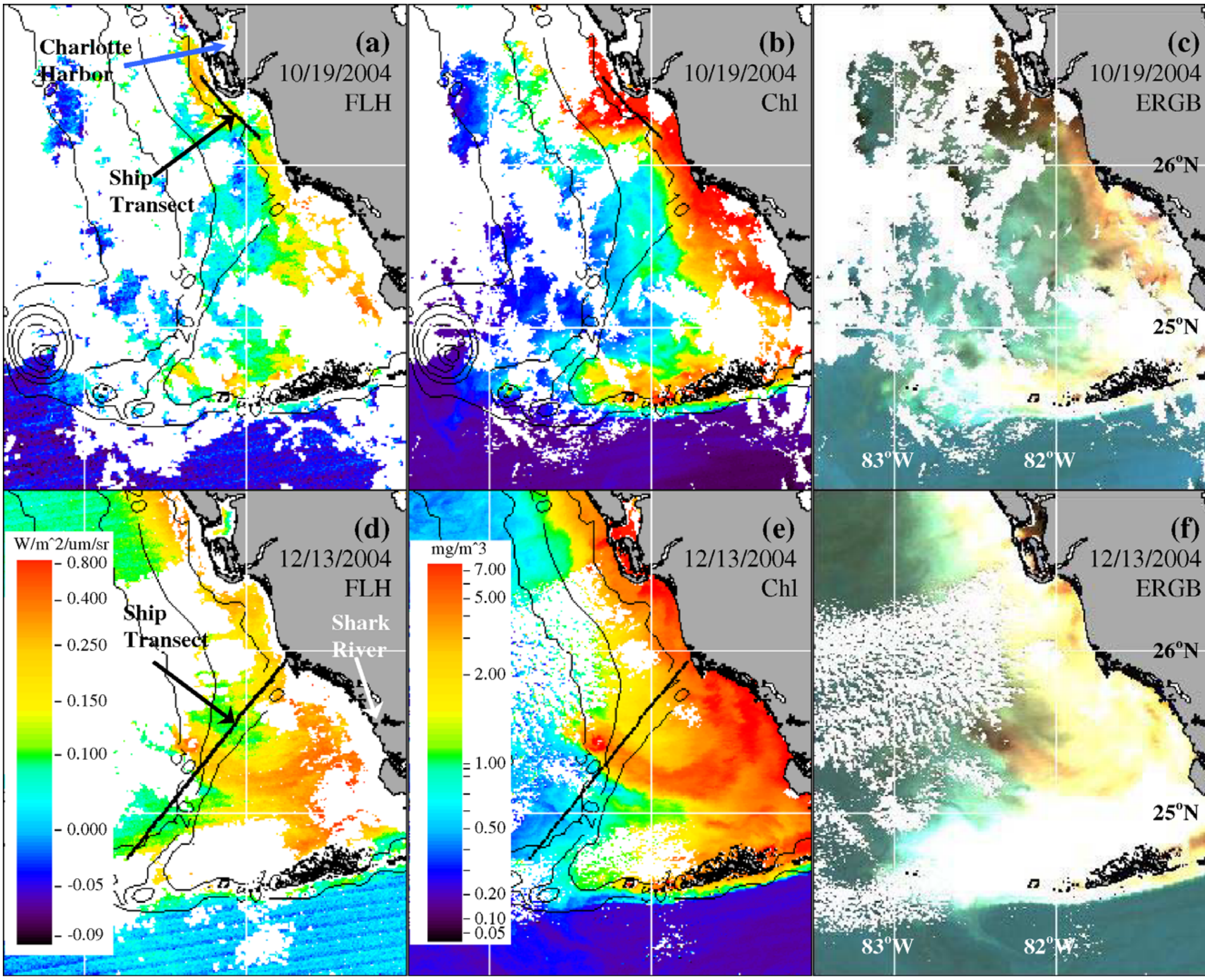

Fig. 1. MODIS/Aqua imagery for SW Florida coastal waters. Left column: Fluorescence Line Height (FLH; W m^{-2} μm^{-1} sr^{-1}); the color scale includes negative values. Middle column: band-ratio chlorophyll concentration (OC3M Chl; mg m^{-3}). Right column: enhanced RGB (ERGB) composite images from water-leaving radiance in three MODIS wavelengths: 551 nm (R), 488 nm (G), and 443 nm (B). MODIS data were collected on 19 October (18:36 GMT) and 13 December (18:44 GMT) 2004. Overlaid on the FLH and Chl images are the approximate isobaths from 10 to 50 m, and near-concurrent ship survey transects.

situ Chl, MODIS FLH, and MODIS Chl along the ship transect for the ±2 h time window. FLH patterns matched the in situ Chl patterns well ($Chl = 1.255 \times (FLH \times 10)^{0.86}$, $r = 0.92$, $n = 77$) across a large range of values and environments, from a pure marine environment (salinity >36) to a coastal environment with freshwater runoff (salinity <35). The MODIS Chl, instead, showed a bias of factors between 3–15 times in situ Chl and lower correlation with in situ data, particularly at high concentrations. The low salinity observations along the coast suggest that CDOM affected the MODIS band-ratio Chl estimates, although possibly shallow bottom (water depth is <10 m) also contributed to the reflectance in the blue and green.

To assess the applicability of the regression equation, $Chl = 1.255 \times (FLH \times 10)^{0.86}$, for similar data range but at other times, we examined a long, cross-shelf, transect (Fig. 1d and e) for the December 2004 cruise, when the time difference with the satellite overpass was less than 6 h (Fig. 3). The MODIS FLH data and the ship survey showed a high chlorophyll band of ~30 km wide that extended from the Shark River mouth to about 25.6°N 82.5°W ($r = 0.79$, $n = 200$). MODIS and SeaWiFS Chl showed lower agreement with in situ Chl ($r = 0.52$ and 0.43, respectively). Nearshore (north of 25.4°N), similar to the results shown in Fig. 2, MODIS and SeaWiFS overestimated Chl by factors of 3–5, while in offshore waters (south of 24.9 °N) MODIS and SeaWiFS underestimated Chl. Using the regression equation established from the October cruise, the mean relative error in the FLH predicted Chl (inset in Fig. 3b) is about 76%, compared with 124% in the MODIS and SeaWiFS band-ratio Chl.

Synoptic patterns seen in the MODIS FLH data showed better agreement with in situ Chl than MODIS or SeaWiFS Chl, regardless of water type. For the range of 0.4 to 4 mg

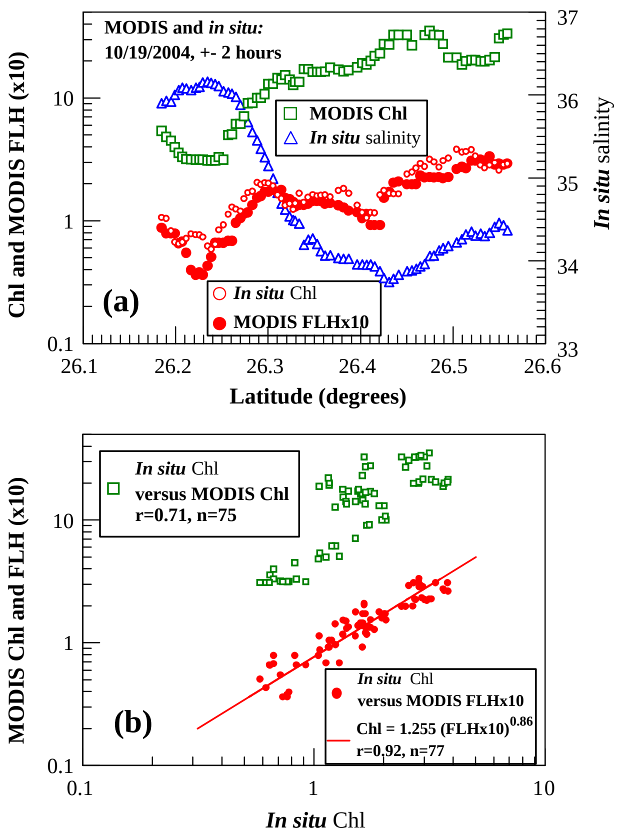

Fig. 2. Biological and physical parameters measured using MODIS and in situ surveys within ±2 h of each other. (a) In situ Chl (mg m^{-3}; calibrated fluorescence data) and salinity, plus MODIS FLH (W m^{-2} μm^{-1} sr^{-1}; to facilitate visual comparison with other properties a factor of 10 was used to construct the figure) and MODIS Chl (mg m^{-3}) along the transect line in Fig. 1a; (b) In situ Chl *vs.* MODIS FLH and MODIS Chl along the transect line. Solid line is the regression between in situ Chl and MODIS FLH.

m^{-3}, the ratio between MODIS FLH and in situ Chl was approximately ~0.1 W m^{-2} μm^{-1} sr^{-1} per mg m^{-3} Chl. For less productive waters the accuracy of MODIS FLH may be reduced due to sensor/algorithm artifacts. Considering that Florida red tides typically have $>5\times10^4$ cells L^{-1} *K. brevis* (corresponding to ~0.5 mg m^{-3} Chl), MODIS FLH should provide an adequate indication of the presence of red tides.

To illustrate the contrast between MODIS FLH and satellite Chl more clearly we present the following example where a red tide was sampled by ship. Fig. 4 shows the MODIS images of 13 November 2004 (18:32 GMT). Data were extracted along two arbitrarily defined transects. One crossed a pigment feature (red color in Fig. 4a) and the second crossed the shelf.

Transect #1 goes from dark coastal waters (high absorption) in the north to the bright water (high backscattering) in the south (Fig. 4c). Along this transect bio-optical properties (FLH and Chl) from MODIS and SeaWiFS showed excellent agreement (Fig. 5a; $r=0.89$, $n=113$). However, satellite-derived Chl values exceeded the FLH-predicted Chl estimates at varying degrees along the transect (MODIS FLH of 0.1 W m^{-2} μm^{-1} sr^{-1} corresponds to ~1 mg m^{-3} Chl).

Along Transect #2, MODIS FLH and satellite Chl differed considerably (Fig. 5b). The FLH data suggested that phytoplankton abundance was relatively homogeneous across the shelf, but MODIS and SeaWiFS Chl suggested that phytoplankton abundance increased >30-fold, from about 0.3 mg m^{-3} Chl offshore to >10 mg m^{-3} Chl nearshore. These trends, again, are likely due to high concentrations of CDOM in coastal waters, as suggested by the *K. brevis* sampling results below. The area of CDOM is apparent as a dark coastal patch in the ERGB image (Fig. 4c). There was a slight increase in SST (~0.3 °C) in areas where FLH was higher. We interpret this to be due to higher absorption of sunlight in dark waters.

3.2. Image series for red tide detection and tracing

In an effort to determine the utility of the satellite-derived FLH images to identify suspicious blooms, we examined the

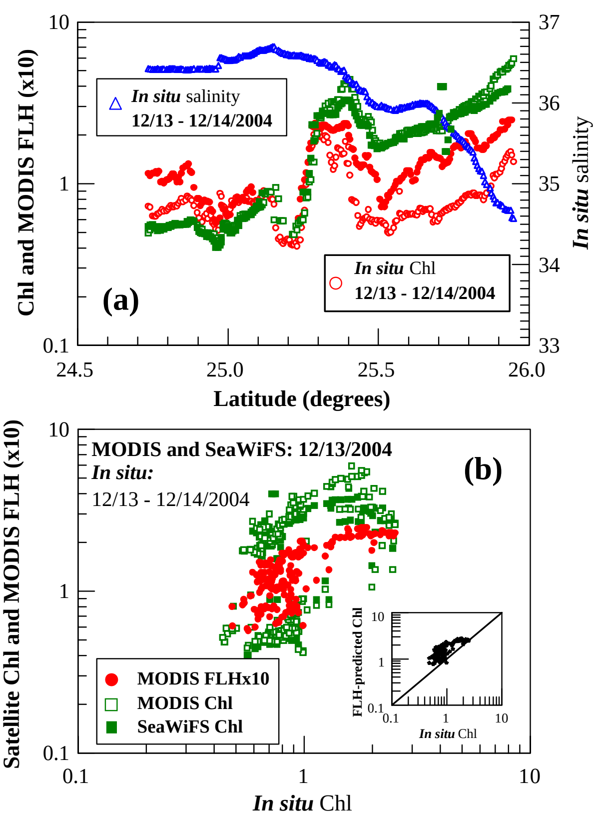

Fig. 3. Similar to Fig. 2, but for the cross-shelf transect as shown in Fig. 1d. Note the time difference between satellite and in situ measurements (up to 6 h), and the addition of concurrent SeaWiFS data. Correlation coefficients between in situ Chl and MODIS FLH, MODIS Chl, and SeaWiFS Chl are 0.79 ($n=200$), 0.52 ($n=223$), and 0.43 ($n=200$), respectively. The inset figure in (b) shows comparison between in situ Chl and MODIS FLH-predicted Chl, using the regression equation $\mathrm{Chl}=1.255\times(\mathrm{FLH}\times10)^{0.86}$, obtained from another cruise in a different but adjacent region (Fig. 2b). FLH is in W m^{-2} μm^{-1} sr^{-1} and Chl is in mg m^{-3}.

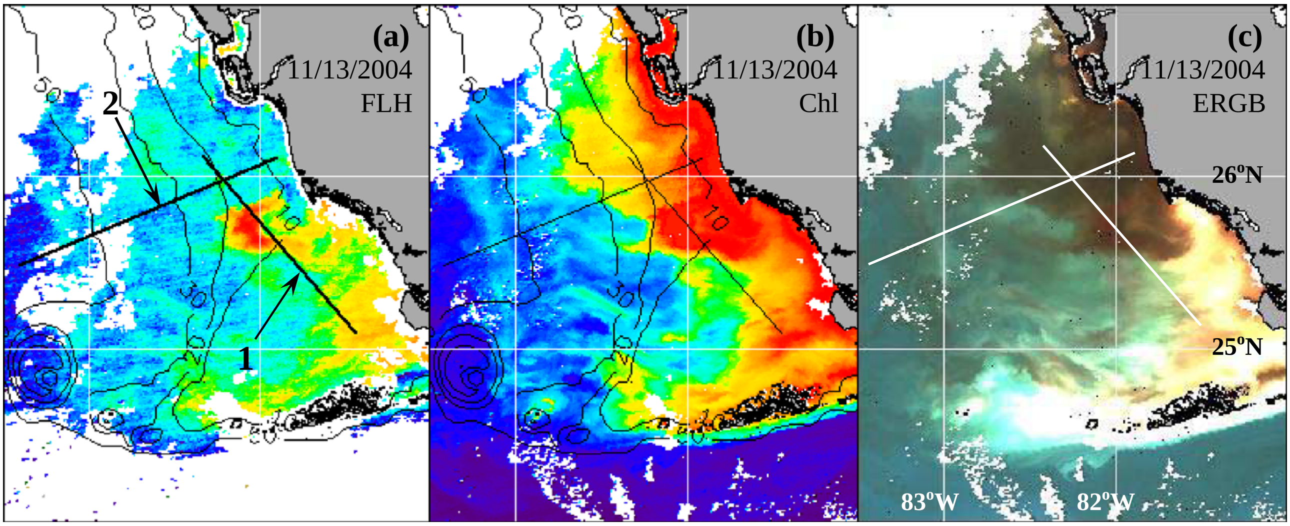

Fig. 4. Similar to Fig. 1, but MODIS/Aqua imagery was obtained on 13 November 2004 (18:32 GMT). Color scales can be found in Fig. 1. Overlaid on the FLH and Chl images are two arbitrary along-coast and cross-shelf transect lines used to extract several parameters (shown in Fig. 5).

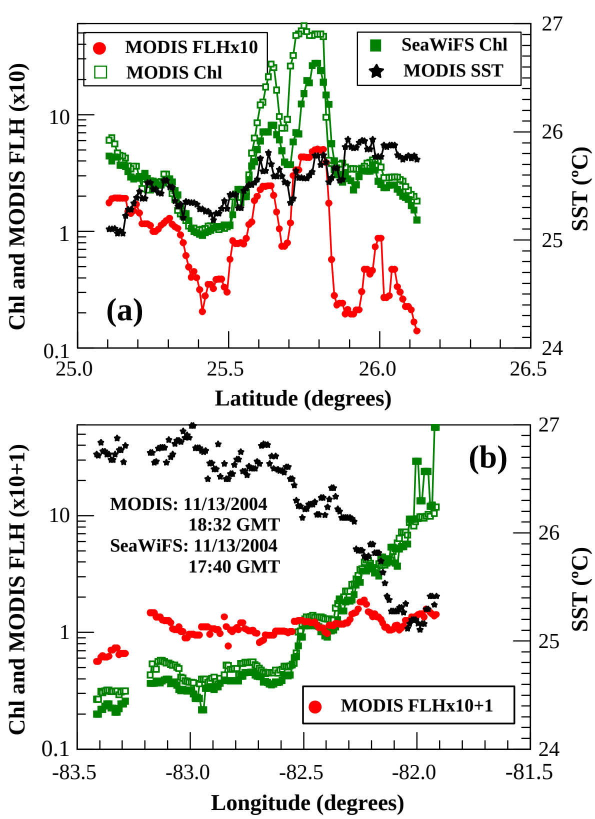

Fig. 5. Biological and physical parameters measured from MODIS and SeaWiFS on 13 November 2004 along two transect lines (Fig. 4). (a) MODIS FLH (W m^{-2} μm^{-1} sr^{-1}), MODIS Chl (mg m^{-3}), SeaWiFS Chl (mg m^{-3}), and MODIS SST (°C) along Transect #1; (b) Same properties along Transect #2. An arbitrary factor of 10 (for Transect #1) and offset of 1 (for Transect #2) were applied to the MODIS FLH data to facilitate comparison with satellite Chl and to plot in log scale. Time difference between the two measurements (SeaWiFS and MODIS) was about 52 min.

MODIS data broadcast real-time from the Aqua and Terra satellites daily during late 2004. Several suspicious patterns were identified with the FLH images in mid-to late October 2004 (red arrows in Fig. 6a and b). In situ data showed that the bloom contained high concentrations (>10^5 cells L^{-1}) of *K. brevis* by mid-late November (Fig. 6d and e), when mortality of large fish (>1 foot long) and of at least four dolphins was reported by local fishermen.

From early November to mid December (Fig. 6c–i), the bloom drifted southward and expanded to form a large curved patch to offshore waters around 25.5 °N 82.5 °W. During subsequent weeks (images not shown) the bloom moved further to the south and formed a continuous band parallel to the Florida Keys.

On 19 October 2004, most waters immediately off Charlotte Harbor did not contain toxic phytoplankton, but a small nearshore patch (marked with a red arrow in Fig. 6a) contained high concentrations of *K. brevis*. Clearly, FLH data alone are insufficient to identify whether a bloom is toxic or not. However, most high-FLH features in the image series were confirmed by the field sampling results to contain medium to high concentrations of *K. brevis*. Similarly, the low-FLH waters were confirmed to contain low or undetectable concentrations of *K. brevis*. Considering the much-larger, spatially coherent features identified by the satellite Chl data, the example suggests that MODIS FLH data provide a better means to detect and trace Florida red tides.

Although MODIS/Terra FLH data have higher noise and more marked image striping, they can often be used in combination with MODIS/Aqua to increase daily coverage (e.g., Hu & Muller-Karger, 2003). Fig. 6h shows an example of MODIS/Terra FLH data (16:23 GMT; MODIS/Aqua data on the same day contains cloud cover), which shows

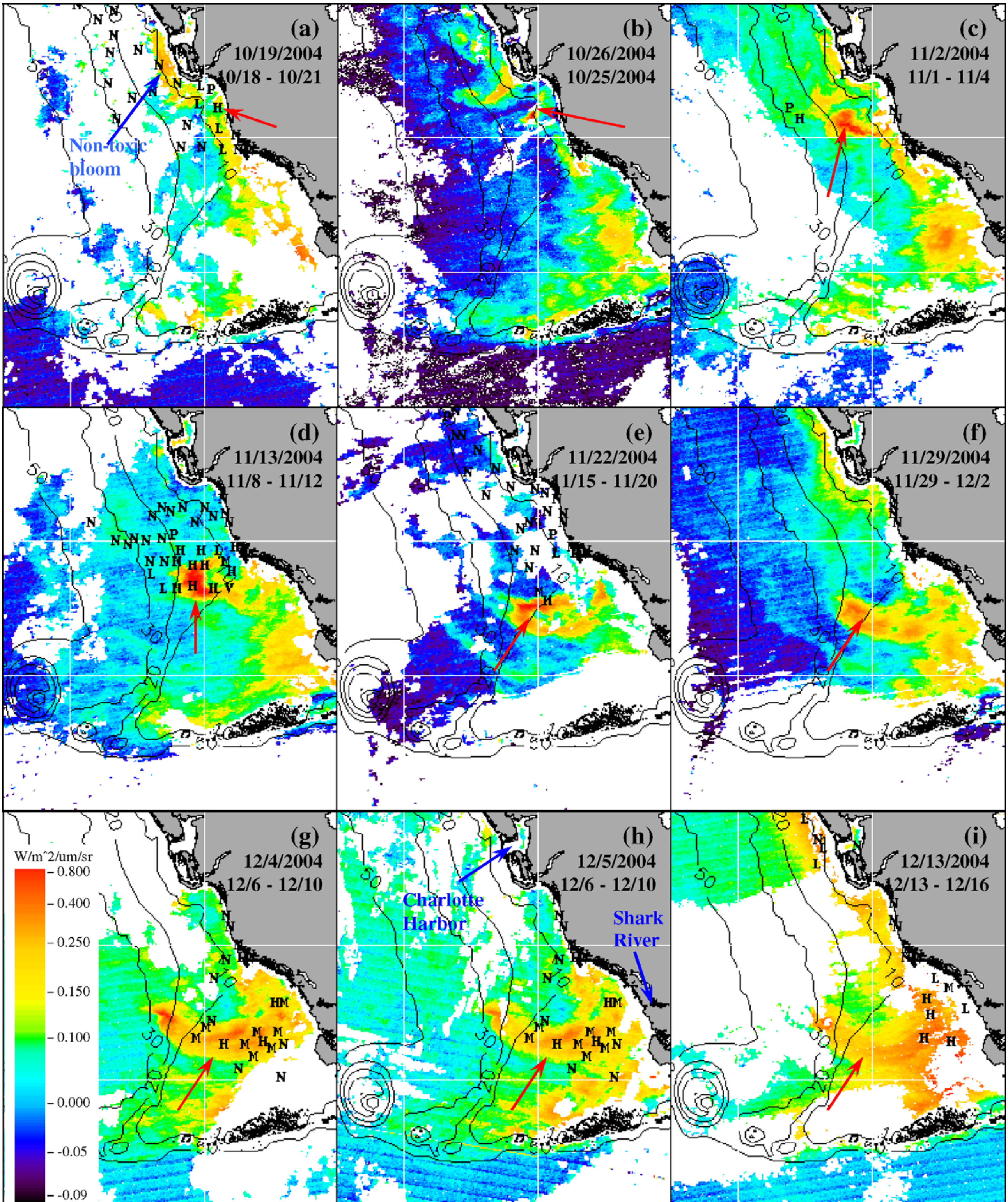

Fig. 6. MODIS FLH image series show the development and progression of a harmful algal bloom or red tide (identified by red arrows). Overlaid on the images are water sample analysis results from the Florida Fish and Wildlife Research Institute (FWRI). The second date on each image indicates the in situ sample collection time. Letters represent different *K. brevis* concentrations in cells L^{-1} as follows: N – not present or below detection limit; P – present ($<10^3$); L – low (between 10^3 and 10^4); M – medium (between 10^4 and 10^5; H – high (between 10^5 and 10^6); V – very high ($>10^6$).

consistent patterns compared with a MODIS/Aqua scene collected the previous day (18:50 GMT, Fig. 6g).

4. Discussion

Satellite ocean color data are valuable to identify anomalous events in the coastal ocean expressed as changes in the color of the water (e.g., SWFDOG, 2002; Hu et al., 2003a; Hu et al., 2004). Proper interpretation of these changes is difficult, however. If we have confidence in the *consistency* of satellite estimates of chlorophyll, even if the *accuracy* is doubtful, then computing the difference between images to assess anomalies can help attribute changes to specific phytoplankton dynamics. Stumpf et al. (2003a) proposed to use the difference between an instantaneous satellite chlorophyll estimate and the mean value of chlorophyll over two previous months, with two weeks in between, as an index to detect suspicious patches that may be potential red tides. This method is now used operationally by NOAA NESDIS (CoastWatch) to issue HAB alerts for west Florida. However, the results are problematic when Chl estimates are not consistent in time. Fig. 7 shows an example of a Chl anomaly image computed using this approach. CDOM-rich waters south of Charlotte Harbor led to overestimates in Chl (Figs. 4b and 6d) and large areas flagged as potential HABs. The MODIS FLH image (Fig. 6d) correctly identified the region of high Chl, which indeed consisted of a HAB.

Estimating Chl with traditional remote sensing techniques in optically complex waters will remain a great challenge to the ocean color community, and it may prove to be an impossible task in many cases (e.g., Hu et al., 2003b), particularly for waters where CDOM rather than phytoplankton dominates the blue-light absorption. The MODIS fluorescence bands were designed to overcome this difficulty by focusing on the red part of the spectrum where chlorophyll fluorescence dominates the total signal, and therefore suffer little from other interferences (CDOM, shallow bottom, and even the atmosphere).

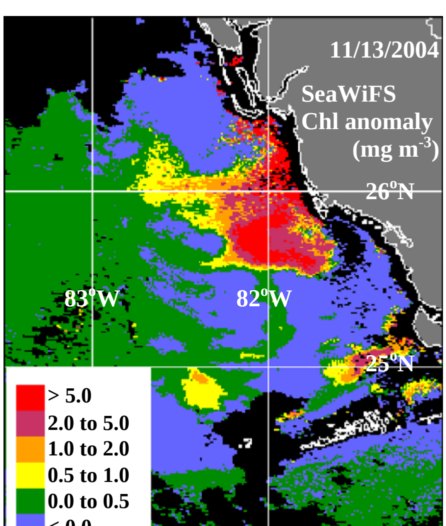

Fig. 7. SeaWiFS Chl anomaly image for 13 November 2004. Chl anomaly is defined as the difference between the current data and a two-month mean two weeks ago. Anomaly of >1 mg m^{-3} indicates potential red tide.

Our results show the advantage of the MODIS FLH data over the traditional satellite Chl data in identifying and tracking blooms (harmful or not). Combined with the ERGB composite imagery from the spectral L_w data, and knowledge of local waters, an operator may be able to identify unambiguously whether a feature is shallow bottom, resuspended sediment, a phytoplankton bloom, or a CDOM-rich plume. It is not really possible to tell whether an identified bloom is toxic or not based on these data alone, but ground observations guided by a bloom alert, and/or familiarity with the environment may provide additional clues. For example, Florida red tides rarely occur in late spring, and the high-FLH patches near the middle Keys or immediately off the Shark River mouth are not likely red tides because other species (e.g., diatoms) may out compete *K. brevis* growth in these nutrient-rich environments.

Examination of the MODIS Level-1 data shows that one digital count of band 14 (676.7 nm) data corresponds to 0.009 W m^{-2} μm^{-1} sr^{-1}. Assuming a conversion factor of 0.1 W m^{-2} μm^{-1} sr^{-1} per mg m^{-3} Chl, MODIS FLH data could theoretically detect Chl differences of ~0.1–0.2 mg m^{-3}. On the other hand, maximum FLH values from a series of MODIS images were found to be ~0.9 W m^{-2} μm^{-1} sr^{-1}, corresponding to 10–20 mg Chl m^{-3} (assuming the same conversion factor). Therefore, there is likely a cap for MODIS FLH values. For higher Chl waters there is a "red shift" in the fluorescence peak to wavelengths as long as 710 nm (e.g., Ruddick et al., 2001), because the "fluorescence" detected by a remote sensor is not a laser-stimulated signal from a water sample, but a solar-stimulated fluorescence of the water column, modulated by water absorption and scattering. Because of the "red shift", FLH derived with the three-band baseline method may be underestimated for highly productive waters. The Medium Resolution Imaging Spectrometer (MERIS) is equipped with a 10-nm band centered at 708.75 nm, which may be used to estimate FLH with a Maximum Chlorophyll Index (MCI) algorithm under these circumstances (Gower et al., 2003).

As advised in Letelier and Abott (1996), MODIS FLH data should be interpreted with caution. Fluorescence efficiency of phytoplankton (i.e., ratio between photons emitted to absorbed) may vary significantly (up to one order of magnitude) both spatially and temporally. Factors affecting variability include taxonomy, nutrient availability, light history, and temperature. In this study, however, high correlation with in situ Chl across various water types and consistent image time-series suggested that the fluorescence efficiency was relatively stable through time and across water types.

The results shown here provide some hope for continuing research and assessment of blooms in coastal ocean waters using MODIS data. However, the VIIRS sensor, to be flown on the NPP (~2006) and then on NPOESS satellites (2012 and beyond), will not measure fluorescence. For long-term continuity, another sensor with fluorescence capability is highly desired.

5. Future work

Several challenges deserve immediate attention to enable the operational application of MODIS FLH data in coastal oceanography. These include:

1) Noise reduction and data normalization. MODIS FLH data show striping (variation in the response among detectors) and significant noise near cloud edges. Further, MODIS FLH data from different seasons are not comparable because of significant differences in incident surface solar irradiance and possibly the fluorescence efficiency. Ideally, fluorescence efficiency should be used for cross-season comparisons. However, due to difficulties in deriving the chlorophyll absorption coefficient in complex coastal environments, fluorescence efficiency estimates may also contain large uncertainties. Therefore, a simple method that uses the surface irradiance as a parameter against which to normalize the data may provide a first-order basis for comparisons across time;
2) Calibration of FLH to chlorophyll concentration (Chl) in various environments. Chl has been used widely as an index for coastal eutrophication. Most resource managers are familiar with this parameter. It is therefore desirable to convert FLH, a relative index for phytoplankton abundance, to Chl;
3) Improved estimates of Chl, independent of the FLH data, because the ratio of fluorescence to Chl may be used as a unique index to separate HABs from other types of blooms (Cannizzaro et al., accepted for publication);
4) Integration of MODIS satellite products into various Coastal Ocean Observing Systems (COOS).

6. Summary and conclusion

MODIS and SeaWiFS data were evaluated and used to study a harmful algal bloom (red tide) event in SW Florida coastal waters between October and December 2004. Comparison with observations collected during near-concurrent field surveys showed that MODIS fluorescence line height (FLH) data provided more reliable information than other traditional satellite products (e.g., chlorophyll concentration estimated from the blue/green band ratio) on the relative distribution of the phytoplankton abundance in this complex coastal environment.

MODIS FLH and chlorophyll concentration measured in situ (Chl, 0.4–4 mg m^{-3}) and within ±2 h of the satellite overpass showed the highest correlation ($r=0.92$, $n=77$) in nearshore waters (depth <10 m), where the water type changed from pure marine, highly saline (salinity >36) water to coastal runoff, low salinity (<35) water. In contrast, correlation between Chl estimated from satellite measurements from both MODIS and SeaWiFS and in situ Chl was significantly lower. Further, the presence of CDOM and shallow bottom are often misinterpreted as Chl, leading to inaccurate and more importantly, inconsistent Chl estimates both spatially and temporally. For example, depending on the time and location, satellite Chl can be either lower than, roughly equal to, or significantly higher (3–15 times) than in situ Chl. Hence, MODIS FLH data can be used as a better index than the satellite Chl to differentiate phytoplankton blooms from other suspicious features such as CDOM-rich plumes. For the area and time period studied, and for the Chl range of ~0.4–4 mg m^{-3}, it is found that FLH of 0.1 W m^{-2} μm^{-1} sr^{-1} is corresponding to about 1 mg m^{-3} Chl.

To test this concept, MODIS FLH image series were used to detect and trace a red tide. Patches with high FLH values (~>0.12 W m^{-2} μm^{-1} sr^{-1}) were often found to contain medium to high concentrations (between 10^4 and 10^6 cells L^{-1}) of the red tide species *K. brevis* in the region. The red tide event was successfully monitored with the MODIS FLH imagery.

Our results show progress towards the first of the two major difficulties in identifying HABs from space: 1) differentiating phytoplankton blooms from other suspicious features; and 2) differentiating HABs from other non-toxic blooms. Familiarity with the regional oceanography may help further identify suspicious patches as HABs. Hence, MODIS FLH imagery, available daily and timely with both Terra (morning passes) and Aqua (afternoon passes), provides an unprecedented tool to monitor the environmental health of the coastal ocean and to guide field sampling efforts. At present, a combination of MODIS FLH, satellite Chl, and enhanced RGB composite can help satellite data interpretation in terms of differentiating blooms, plumes, sediments, and shallow bottom. We strongly recommend that these strategies be integrated in the various coastal ocean observing systems.

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References

Anderson, D. M. (1995). ECOHAB: The Ecology and Oceanography of Harmful Algal Blooms, a national research agenda. *Woods Hole Oceanog*. Woods Hole, MA: Institute, 67 pp.

Arnone, R. A., Martinolich, P., Gould, R. W., Jr., Stumpf, R., & Ladner, S. (1998). Coastal optical properties using SeaWiFS. Ocean Optics XIV, Kailua Kona, Hawaii, USA, November 10–13, 1998. *SPIE Proceedings*.

Bailey, S. W., McCLain, C. R., Werdell, P. J., & Schieber, B. D. (2000). In J. Hooker, & J. Firestone (Eds.), Normalized water-leaving radiance and chlorophyll *a* match-up analyses. *NASA/TM-2000-206892*, *Vol. 10* (pp. 45–52), ch. 7.

Cannizzaro, J. P., Carder, K. L., Chen, F. R., Heil, C. A., Vargo, G. A. (accepted for publication). A novel technique for detection of the toxic dinoflagellate *Karenia brevis* in the Gulf of Mexico from remotely sensed ocean color data. *Continental Shelf Research*.

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

Esaias, W. E., Abbott, M. R., Barton, I., Brown, O. B., Campbell, J. W., Carder, K. L., et al. (1998). An overview of MODIS capabilities for ocean science observations. *IEEE Transactions on Geoscience and Remote Sensing*, *36*, 1250–1265.

Evens, T. J., Kirkpatrick, G. J., Millie, D. F., Chapman, D. J., & Schofield, O. M. E. (2001). Photophysiological responses of the toxic red-tide dinoflagellate *Gymnodinium breve* (Dinophyceae) under natural sunlight. *Journal of Plankton Research*, *23*, 1177–1193.

Fischer, J., & Kronfeld, U. (1990). Sun-stimulated chlorophyll fluorescence: 1. Influence of oceanic properties. *International Journal of Remote Sensing*, *11*, 2125–2147.

Gordon, H. R., & Wang, M. (1994). Retrieval of water-leaving radiance and aerosol optical thickness over the oceans with SeaWiFS: A preliminary algorithm. *Applied Optics*, *33*, 443–452.

Gower, J. F. R., & Borstad, G. A. (1981). The information content of different optical spectral ranges for remote chlorophyll fluorescence measurements. In J. F. R. Gower (Ed.), *Oceanography from space* (pp. 329–338). New York: Plenum.

Gower, J. F. R., & Borstad, G. A. (2004). On the potential of MODIS and MERIS for imaging chlorophyll fluorescence from space. *International Journal of Remote Sensing*, *25*, 1459–1464.

Gower, J. F. R., King, S., Yan, W., Borstad, G., & Brown, L. (2003). Use of the 709 nm band of MERIS to detect intense plankton blooms and other conditions in coastal waters. *Proc. MERIS User Workshop, Frascati, Italy, 10 – 13 November 2003.*

Hoge, F. E., Swift, R. N., & Yungel, J. K. (1986). Active–passive airborne ocean color measurements: instrumentation. *Applied Optics*, *25*, 48–57.

Hoge, F. E., Lyon, P. E., Swift, R. N., Yungel, J. K., Abbott, M. R., Letelier, R. M., et al. (2003). Validation of Terra-MODIS phytoplankton chlorophyll fluorescence line height: I. Initial airborne lidar results. *Applied Optics*, *42*, 2767–2771.

Hu, C., Carder, K. L., & Muller-Karger, F. E. (2001). How precise are SeaWiFS ocean color estimates? Implications of digitization-noise errors. *Remote Sensing of Environment*, *76*, 239–249.

Hu, C., Hackett, K. E., Callahan, M. K., Andréfouët, S., Wheaton, J. L., Porter, J. W., et al. (2003a). The 2002 ocean color anomaly in the Florida Bight: a cause of local coral reef decline? *Geophysical Research Letters*, *30*(3), 1151, doi:10.1029/2002GL016479.

Hu, C., Lee, Z. P., Muller-Karger, F. E., & Carder, K. L. (2003b). Application of an optimization algorithm to satellite ocean color imagery: A case study in Southwest Florida coastal waters. In J. Frouin, Y. Yuan, & H. Kawamura (Eds.), SPIE Proceedings. *Ocean Remote Sensing and Applications*, *vol. 4892* (pp. 70–79). Bellingham, WA: SPIE.

Hu, C., Luerssen, R., Muller-Karger, F. E., Carder, K. L., Heil, C. A. (Submitted for publication). In search of red tides: Observations on the west Florida shelf. *Cont. Shelf Res.*

Hu, C., & Muller-Karger, F. E. (2003). MODIS monitors the Florida's ocean dispersal of the Piney Point Phosphate treated wastewater. *The Earth Observer*, *15*(6), 21–23.

Hu, C., Muller-Kager, F. E., Vargo, G. A., Neely, M. B., & Johns, E. (2004). Linkages between coastal runoff and the Florida Keys ecosystem: A study of a dark plume event. *Geophysical Research Letters*, *31*, L15307, doi:10.1029/2004GL020382.

Kahru, M., & Mitchell, B. G. (1998). Spectral reflectance and absorption of a massive red tide off Southern California. *Journal of Geophysical Research*, *103*(C10), 21,601–21,609.

Kirkpatrick, G. J., Millie, D. F., Moline, M. A., & Schofield, O. (2000). Optical discrimination of a phytoplankton species in natural mixed populations. *Limnology and Oceanography*, *45*(2), 467–471.

Letelier, R. M., & Abott, M. R. (1996). An analysis of chlorophyll fluorescence algorithms for the Moderate Resolution Imaging Spectrometer (MODIS). *Remote Sensing of Environment*, *58*, 215–223.

Lohrenz, S. E., Fahnenstiel, G. L., Kirkpatrick, G. J., Carroll, C. L., & Kelly, K. A. (1999). Microphotometric assessment of spectral absorption and its potential application for characterization of harmful algal species. *Journal of Phycology*, *35*, 1438–1446.

McClain, C. R., Cleave, M. L., Feldman, G. C., Gregg, W. W., Hooker, S. B., & Kuring, N. (1998). Science quality SeaWiFS data for global biosphere research. *Sea Technology*, *39*, 10–16.

Millie, D. F., Schofield, O., Kirkpatrick, G. J., Johnsen, G., Tester, P. A., & Vinyard, B. T. (1997). Phytoplankton pigments and absorption spectra as potential 'Biomarkers' for harmful algal blooms: A case study of the Florida red-tide dinoflagellate, *Gymnodinium breve*. *Oceanographie*, *42*, 1240–1251.

Morton, R. A., & Burklew, M. A. (1969). Florida shellfish toxicity following blooms of dinoflagellate *Gymnodium breve*. *Florida Department of Natural Resources Marine Laboratory, Tech. Ser.*, *60*, 26.

Neville, R. A., & Gower, J. F. R. (1977). Passive remote sensing of phytoplankton via chlorophyll fluorescence. *Journal of Geophysical Research*, *82*, 3487–3493.

O'Reilly, J. E., Maritorena, S., Siegel, D. A., O'Brien, M. C., Toole, D., Chavez, F. P., et al. (2000). Ocean color chlorophyll a algorithms for SeaWiFS, OC2, and OC4: Version 4. In B. Hooker, & R. Firestone (Eds.), SeaWiFS Postlaunch Tech. Report Series. *NASA Technical Memorandum 2000-206892*, *vol. 11* (p. 2000).

Ruddick, K. G., Gons, H. J., Rijkeboer, M., & Tilstone, G. (2001). Optical remote sensing of chlorophyll *a* in case 2 waters by use of an adaptive two-band algorithm with optical error properties. *Applied Optics*, *40*, 3575–3585.

Schofield, O., Grzymski, J., Bissett, W. P., Kirkpatrick, G. J., Millie, D. F., Moline, M., et al. (1999). Optical monitoring and forecasting systems for Harmful Algal Blooms: Possibility or pipe dream? *Journal of Phycology*, *35*, 1477–1496.

Shoaf, W. T., & Lium, B. W. (1976). Improved extraction of chlorophyll *a* and *b* from algae using dimethyl sulfoxide. *Limnology and Oceanography*, *21*, 926–928.

Steidinger, K. A., & Haddad, K. (1981). Biologic and hydrographic aspects of red tides. *Bioscience*, *31*(11), 814–819.

Steidinger, K. A., & Ingles, R. M. (1972). Observations on the 1971 summer red tide in Tampa Bay. *Florida Environmental Letters*, *3*(4), 271–277.

Steidinger, K. A., & Joyce, E. A. (1973). Florida red tide. *Florida Department of Natural Resources Report No. 17* (p. 26). St. Petersburg, Florida: Marine Research Department.

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 E. Anderson, D. Cembella, & M. Hallengraff (Eds.), *Physiological ecology of harmful algal blooms* (pp. 135–153). New York: Springer-Verlag.

Stumpf, R. P., Culver, M. E., Tester, P. A., Tomlinson, M., Kirkpatrick, G. J., Pederson, B. A., et al. (2003a). Monitoring *Karenia brevis* blooms in the Gulf of Mexico using satellite ocean color imagery and other data. *Harmful Algae News*, *35*, 1–14.

Stumpf, R. P., Arnone, R. A., Gould Jr., R. W., Martinolich, P. M., & Martinuolich, V. (2003b). A partially coupled ocean-atmosphere model for retrieval of water-leaving radiance from SeaWiFS in coastal waters. In S. B. Hooker, & E. R. Firestone (Eds.), SeaWiFS Postlaunch Tech. Report Series. *NASA Technical Memorandum, 2003-206892*, *vol. 22* (p. 74).

SWFDOG. (2002). Satellite images track "black water" event off Florida coast. *EOS Transactions American Geophysical Union*, *83*, 281,285.

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

Tomlinson, M. C., Stumpf, R. P., Ransibrahmanakul, V., Turby, E. W., Kirkpatrick, G. J., Pederson, B. A., et al. (2004). Evaluation of the use of SeaWiFS imagery for detecting Karenia brevis harmful algal blooms in the eastern Gulf of Mexico. *Remote Sensing of Environment*, *91*, 293–303.

Walsh, J. J., & Steidinger, K. A. (2001). Saharan dust and Florida red tides: The cyanophyte connection. *Journal of Geophysical Research*, *106*, 11,597–11,612.

Williams, J., & Ingles, R. M. (1972). Ecological note on Gonyaulax momlata (Dinophyceae). *Florida Department of Natural Rescources Marine Laboratory Leaf. Ser.*, *1*(Pt 1). No. 5, 12 pp.