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Detection of Florida "red tides" from SeaWiFS and MODIS imagery

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Abstract: Central west Florida shelf (CWFS) has a nearly annual occurrence of "red tides". Two current operating ocean color sensors (SeaWiFS and MODIS) were used to identify a bloom of the toxic dinoflagellate *Karenia brevis* during August 2001. Chlorophyll concentrations alone cannot be used to distinguish taxonomic groups, so other optical means must be brought into play to discriminate phytoplankton. Thus, a preexisting technique based on high chlorophyll concentration and low particulate backscatter, previously applied to SeaWiFS, was tested on MODIS to detect *K. brevis*. Moreover, standard global chlorophyll algorithms , in the CWFS, can have errors, of either sign, so the performance of a new methodology based only on a single water leaving radiance band was applied to measurements from both sensors. The results showed that both approaches worked similarly and satisfactorily, but the new methodology was able to produce more consistent outcomes between both sensors. This is extremely encouraging for across-sensor applications in other "red tide" events.

Key words: Harmful algae bloom, red tide, central west Florida shelf, ocean color, SeaWiFS, MODIS, floração de algas tóxicas, maré vermelha, plataforma continental oeste da Florida, cor do oceano.

1. Introduction

Due to water discoloration, the term "red tide" is quite often used to describe harmful algae blooms (henceforth HABs). The adverse threats to public well-being (Backer et al., 2003), economic losses (Kusek et al., 1999), marine wildlife kill (Shumway et al, 2003) and coastal aesthetics have led to increased attention from the scientific community, environmental menagers and the general public (Van Dolah, 2000). The first official HAB in U.S. Gulf of Mexico waters was reported in 1844 (Magaña et al., 2003). They often occur along the central west Florida shelf (hereafter CWFS; **Figure 1a**), and the major causative organism is the dinoflagellate *Karenia brevis*, formerly *Gymnodinium breve* and *Ptychodiscus brevis* (**Figure 1b**). This organism produces brevetoxins (PbTx's) that can adversely affect public health via inhalation (Cheng et al., 2005) and by ingestion of tainted seafood, causing the non-lethal Neurotoxic Shellfish Poisoning (Kirkpatrick et al., 2004). The blooming season typically begins in late boreal summer (~August) and persists until early boreal spring (~April) with nearly annual incidence (Tomlinson et al., 2004). Consequently, monitoring the quality of the CWFS water is of great interest.

Ocean color sensors on satellites are a valuable tool for taking measurements of the marine biosphere, covering large areas and allowing a synoptic scene to be obtained on a regular basis (daily revisits). Some algae blooms tend to concentrate near or at the ocean surface and can cause water discoloration (Heil 1986). In addition, surface chlorophyll-a concentration (chl-a) can be derived via remote sensing observations (e.g. Carder et al., 1999), and many studies have investigated the distribution of phytoplankton (e.g. Tang et al., 1998). However, since it is present in all sorts of plants, it cannot be used as a unique tracer, and satellite-derived chl-a spectral signature alone is not sufficient to permit confident classification among phytoplankton species (Garver et al., 1994). As a result, other spectral features or optical properties (e.g. backscattering or absorption) must be invoked to discriminate (flag) distinct algae communities (Schofield et al., 1999).

On the other hand, remote sensing imagery has the potential to provide researchers with algal taxonomic discrimination once a unique bio-optical signature is established and specific algorithms are developed (e.g. coccolithophore, Brown and Yoder (1994); Trichodesmium spp., Subramaniam et al. (2002)). Furthermore, many studies are often found in the literature relating chl-a with possible HABs via remote sensing data (e.g. Haddad, 1982). Tester and Stumpf (1998) present a description of some satellite capabilities to monitor HABs. Prior studies have helped elucidate the physics and biogeography of phytoplankton blooms and HABs, but to date only a few (Maritorena and Siegel, 2005) have tackled a multi-ocean color investigation for ecological analysis.

The objectives of this investigation are based on two of the most widely used current orbital ocean color sensors: the Sea-viewing Wide Field-of-view Sensor (SeaWiFS; e.g. Hooker et al., 1992) and the Moderate Resolution Imaging Spectroradiometer (MODIS; Esaias et al., 1998). Since measurements of the color of the ocean are taken in the visible part of the electromagnetic spectrum (400-700 nm), they are strongly dependent on clear skies. Clouds may limit the usable images to one or two per week. Thus, one of the goals of this investigation is to overcome this weakness by testing the combined use of these sensors to maximize temporal sampling and increase the probability of acquiring valid data. This investigation also aims to apply to MODIS a preexisting technique to detect CWFS HABs previously applied to SeaWiFS (Cannizzaro, 2004). Ultimately, this research intends to test, on both sensors, the performance of a new methodology to identify the occurrence of HABs.

In view of the fact that satellite-borne measurements are able to enhance ship surveys reducing timelines in finding surface features (i.e. eddies or upwelling), if the reconnaissance of HABs becomes possible, resource managers can better plan mitigation action plans. In summary, the overall aim of this study is to thoroughly exploit the feasibility of using multiple satellite sensors to qualitatively distinguish non-bloom waters from the CWFS HAB.

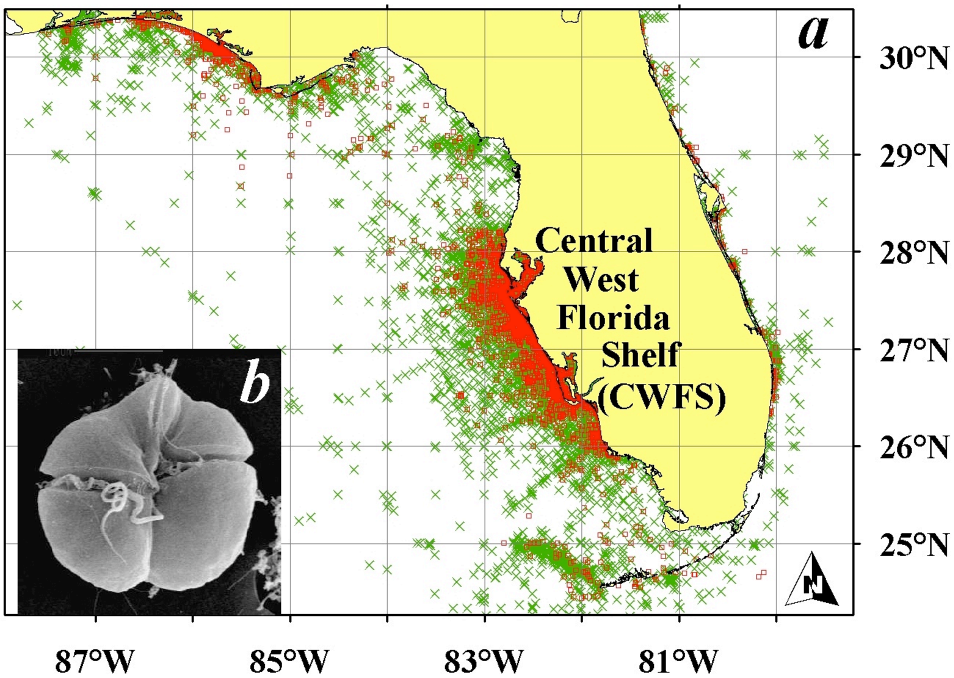

Figure 1: Historical database of the CWFS HAB from 1957 to 2002 (FWRI, 2002).
a) Non-bloom (x) and "red tide" (□) sampling location. ***b***) The dinoflagellate *Karenia brevis*.

2. Background theory

The intrinsic color of the ocean is usually radiometrically described in terms of the remote sensing reflectance, $R_{rs}(\lambda)$, measured just above the sea surface, defined as the upwelling radiance (or water-leaving radiance, $L_w(\lambda)$) normalized by the downwelling solar irradiance ($E_d(\lambda)$). In a simplified manner, $R_{rs}(\lambda)$ depends on inherent optical properties (IOPs) of the water, i.e., total backscatter ($b_b(\lambda)$) and absorption ($a(\lambda)$) coefficients (Kirk, 1994), and can be expressed as:

$$R_{rs}(\lambda) = L_w(\lambda) / E_d(\lambda) \approx 0.083 \ \{b_b(\lambda) / a(\lambda)\} \quad (1)$$

IOPs can be partitioned into optically active constituents (OACs): water molecules (w; constant and known (Smith and Baker, 1981)), particles (p; sum of phytoplankton and detritus) and colored dissolved organic matter (CDOM). Because OAC concentrations change in time and space, the color of the ocean (i.e. $R_{rs}(\lambda)$) will vary as well. The $b_b(\lambda)$ and $a(\lambda)$ can be calculated as follows:

$$b_b(\lambda) = b_{bw}(\lambda) + b_{bp}(\lambda) \quad (2)$$

$$a(\lambda) = a_w(\lambda) + a_p(\lambda) + a_{CDOM}(\lambda) \quad (3)$$

Satellite ocean color sensors measure the total radiance in discrete bands ($L_{sat}(\lambda)$), but around 90% of the signal is due to atmospheric effects, so corrections must be applied in order to retrieve $L_w(\lambda)$ (e.g. Gordon, 1997). Hence, with certain assumptions (Deschamps et al., 1983), $L_{sat}(\lambda)$ can be described as the sum of $L_w(\lambda)$ and atmospheric radiances ($L_{sky}(\lambda)$):

$$L_{sat}(\lambda) = T \, L_w(\lambda) + L_{sky}(\lambda) \quad (4)$$

where T is the atmospheric transmittance. Therefore, the values of $L_w(\lambda)$ along with additional bio-optical algorithms (Gordon et al., 1983) are in turn used to estimate geophysical parameters, such as chl-a. These derived parameters, or $L_w(\lambda)$, or $R_{rs}(\lambda)$, can be subsequently employed on ecological studies such as this.

3. Data and methods

SeaWiFS (launched on August 1997) is onboard the OrbView-2 satellite. Level 1A merged local area coverage (MLAC; 30 August 2001; **Figure 2**) with full resolution (~1 km^2) was acquired from the Ocean Color Web (http://oceancolor.gsfc.nasa.gov/). MODIS flies on board two satellites (Terra and Aqua, launched on December 1999 and May 2002, respectively). Only MODIS-Terra was used on this investigation, and level 1B local area coverage (LAC; with ~1 km^2 of spatial resolution; 29 August 2001; **Figure 2**) was downloaded from the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center's (GSFC) Distributed Active Archive Center (DAAC; http://disc.sci.gsfc.nasa.gov/). They have similar ocean color bands, but those of MODIS are narrower.

Images were processed at the University of Miami, Rosenstiel School of Marine and Atmospheric Science Remote Sensing Laboratory (RRSL) using the most up-to-date algorithms and software (NASA SeaWiFS Data Analysis System, SeaDAS version 5.0.2) with default options and only the best quality flag data (0; good). The Garver-Siegel-Maritorena (GSM01; Maritorena et al., 2002) semi-analytical ocean color algorithm was used to derive $b_{bp}(\lambda)$, and for chl-a estimations, the global band-ratio algorithms were employed (OC4; SeaWiFS and OC3; MODIS; O'Reilly et al., 2000).

Two approaches were considered to detect a CWFS HAB at the end of August 2001 (**Figure 2**). The fist technique (Cannizzaro, 2004; henceforth *Canz*) is based on the fact that the $b_{bp}(\lambda)$ was observed to decrease the $R_{rs}(\lambda)$ from non-bloom to "red tide" conditions. Hence, *Canz* suggest a classification scheme criteria to flag *K. brevis* blooms whenever levels of $b_{bp}(550)$ are lower than the Morel (1988) $b_{bp}(550)$ and chl-a values are high (> 1.5 mg/m^3). Since $b_{bp}(\lambda)$ and chl-a are not directly retrieved from satellite measurements, and because the CWFS chl-a retrieved from SeaWiFS and MODIS can be significantly in errors (Hu et al., 2005), the performance of a new methodology (*Cgus*, which takes into account only a single $L_w(550)$ band) was also applied to both sensors. In *Cgus*, whatsoever falls below the Morel (1988) scatter, b(550), is taken as a bloom of *K. brevis*. The main idea behind these approaches is that due to reducing grazing effects there is not as much detritus, which reduces $b_{bp}(\lambda)$ and $b(\lambda)$.

An *in situ* dataset of *K. brevis* concentration (cells per liter) was obtained from the Fish and Wildlife Research Institute HAB historical database CD-ROM (FWRI, 2002). Since blooms can last more than a week, and because we want to carry a qualitative analysis, a relaxed match-up window of nine days (from 25 August 2001 to 2 September 2001) was employed. Cell count was broken into distinct groups: below 10^4 cells/l (non-bloom) and above 10^4 cells/l ("red tide").

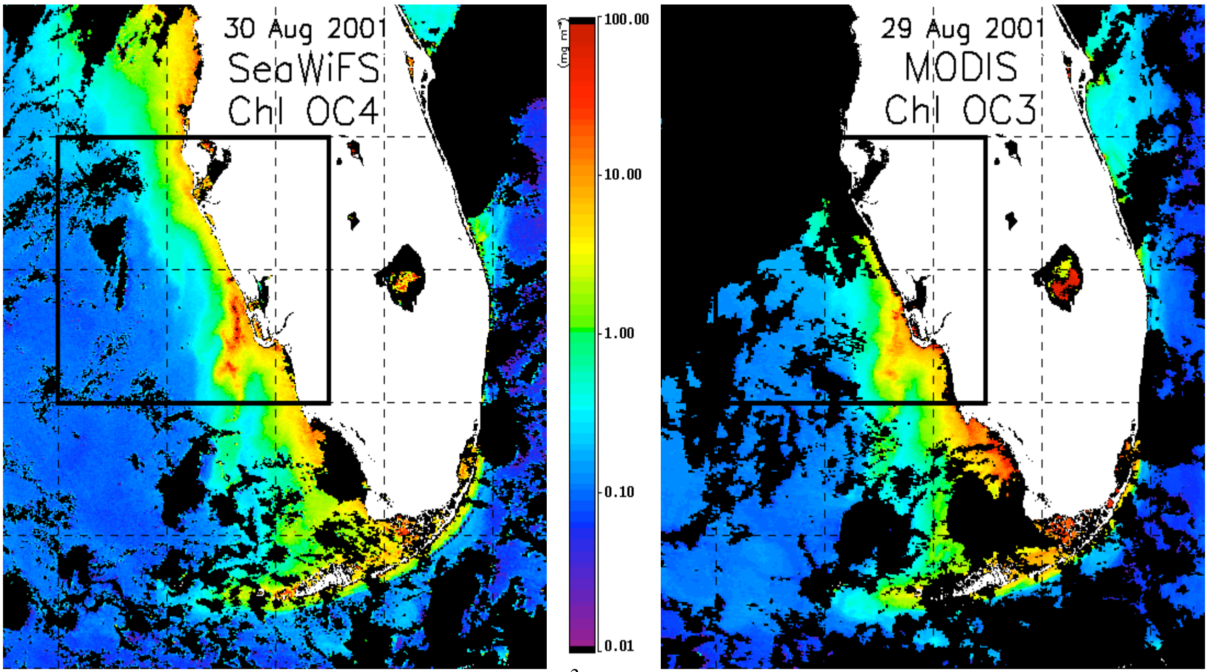

Figure 2: Chlorophyll concentrations (mg/m^3) from SeaWiFS (*left*) and MODIS-Terra (*right*). "Red tides" algorithms were applied on the outlined area (see **Figure 3**).

4. Results and discussions

Firstly, we replicate the *Canz* results using the same SeaWiFS day (30 August 2001). Then we applied our modified algorithm to the MODIS image from the day before (29 August 2001). The similarities in the two distributions are indeed reassuring. **Figure 3** depicts the envelopes of the bloom area (from the outlined area in **Figure 2**) derived from both sensors (SeaWiFS; **Figure 3a**, **3b** and MODIS; **Figure 3b**, **3c**) and using both algorithms (*Canz*; **Figure 3a**, **3c** and *Cgus*; **Figure 3b**, **3d**). It is clear that most of the "red tide" (□) match-ups fall inside the shaded envelopes created by the algorithms, and that the great majority of the non-blooms (x) are indeed outside of the envelopes.

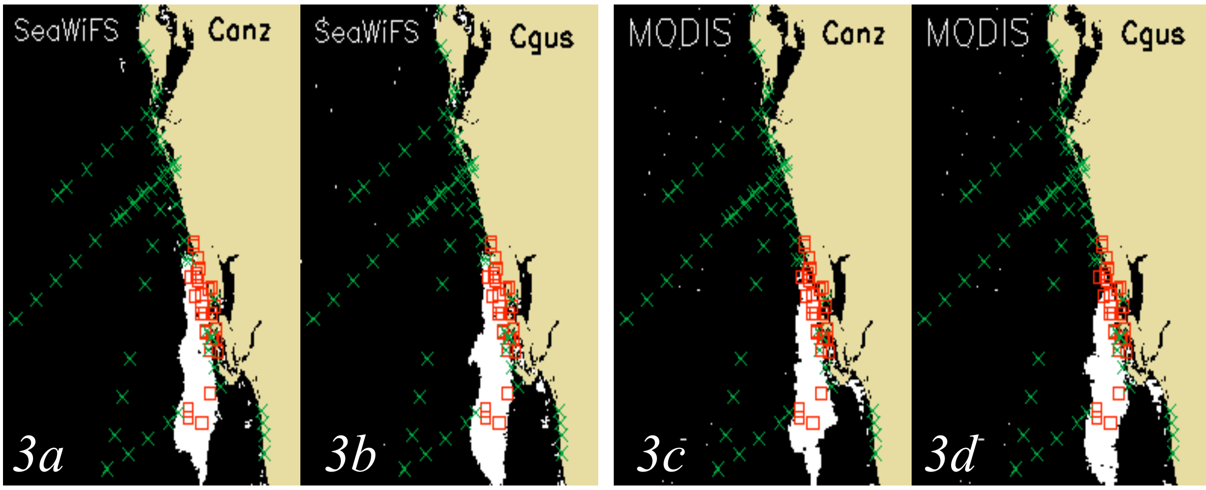

Figure 3: Outlined area in **Figure 2** showing "red tide" envelopes (white), with *in situ* measurements from 25 August 2001 to 2 September 2001 overlaid, where *K. brevis* < 10^4 cells/l (x non-bloom) and *K. brevis* > 10^4 cells/l (□ "red tide"). ***3a, 3b***) from SeaWiFS (30 August 2001), ***3c, 3d***) from MODIS-Terra (29 August 2001), ***3a, 3c***) *Canz* (chl-a > 1.5 mg/m^3 and $b_{bp}(\lambda)$ < Morel (1988) $b_{bp}(550)$), ***3b, 3d***) *Cgus* ($L_w(\lambda)$ < Morel (1988) b(550)).

Figure 4 displays the *Canz* relationship between $b_{bp}(\lambda)$ versus chl-a. In a quantitative analysis, when SeaWiFS was used, *Canz* was able to flag 70% of the "red tide" matching pairs and up to 94% of the non-blooms. MODIS *Canz*'s outcome was better for "red tide" detection (100%), but less reliable for the non-blooms (70%). **Figure 5** presents *Cgus* plots between $L_w(\lambda)$ and chl-a, where both sensors behaved similarly with around 95% accuracy for "red tide" identification and about 85% for non-bloom cases. **Table 1** summarizes the statistical values from both approaches and also shows the observed false positive and false negative cases.

Cgus presented more consistent outcomes between sensors, what encourages further across-sensor applications. Thus, *Cgus* should be tested on more "red tide" events (e.g. Hu et al. (submitted) that used *Canz* technique with a historical SeaWiFS dataset). Also, the use of band-ratio algorithms (e.g. Cannizzaro et al., (2002) based on three $R_{rs}(\lambda)$ bands) to detect HABs is preferable over single band algorithms (i.e. *Cgus*) to minimize residual uncertainties in the atmospheric correction.

Originally, *Canz* used the Carder algorithm (Carder et al., 1999) for $b_{bp}(\lambda)$ and chl-a. When $b_{bp}(\lambda)$ was retrieved from SeaWiFS using Carder algorithm, successful "red tide" detection increased to 90%. The MODIS image used produced very few valid values for Carder algorithm. Thus, in order to compare both sensors, $b_{bp}(\lambda)$ GSM01 was used instead. Nevertheless, since *Canz* had 100% of confidence on MODIS with the $b_{bp}(\lambda)$ GSM01, it is probable that if Carder algorithm were available, the results would be the same or even better.

5. Summary and conclusions

We have applied two distinct approaches (*Canz* and *Cgus*) to detect CWFS HABs using to two current operational ocean color sensors (SeaWiFS and MODIS). The algorithms were corroborated with *in situ* measurements.

The success of the two approaches to delineate the CWFS "red tide" at the end of August 2001 is important for at least three reasons. First and foremost, because it demonstrates another way to depict *K. brevis* blooms through satellite imagery; this encourages further analysis of a broader "red tide" dataset. Secondly, because the outcomes of the "red tide" envelopes were very similar between both sensors; this demonstrates that multiple-sensor monitoring of HABs is possible. And, finally, since SeaWiFS already has gone beyond the five-years designed lifetime, we have demonstrated the potential for continuity of measurements across the successive ongoing ocean color missions (http://www.ioccg.org/sensors_ioccg.html).

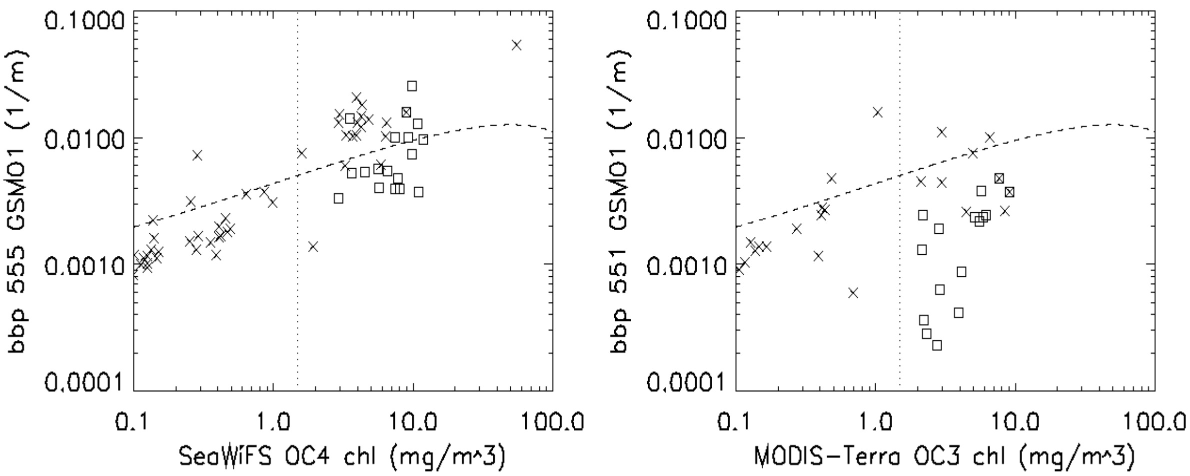

Figure 4: *Canz* (chl-a > 1.5 mg/m^3 and $b_{bp}(\lambda)$ < Morel (1988) $b_{bp}(550)$),
where everything to the right of the dotted line (··· which is 1.5 mg/m^3 of chl-a) and
below the dashed line (--- which is Morel (1988) $b_{bp}(550)$) should be "red tide".
SeaWiFS (30 August 2001; *left*) and MODIS-Terra (29 August 2001; *right*).
K. brevis < 10^4 cells/l (x non-bloom) and *K. brevis* > 10^4 cells/l (□ "red tide"),
match-ups from 25 August 2001 to 2 September 2001.

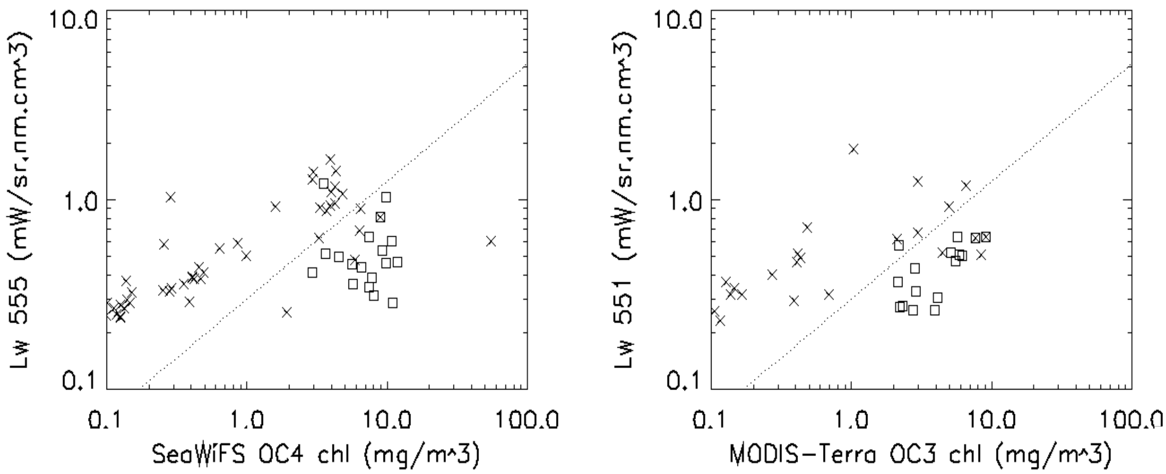

Figure 5: *Cgus* ($L_w(\lambda)$ < Morel (1988) b(550)),
where everything below dotted line (··· which is Morel (1988) b(550)) should be "red tide".
SeaWiFS (30 August 2001; *left*) and MODIS-Terra (29 August 2001; *right*).
K. brevis < 10^4 cells/l (x non-bloom) and *K. brevis* > 10^4 cells/l (□ "red tide"),
match-ups from 25 August 2001 to 2 September 2001.

Table 1: Statistical results of the two tested algorithms to detect CWFS *K. brevis* blooms. Denominators are valid match-ups, and between parentheses is the percentage of occurrence. HAB (red), false positive (blue), non-bloom (green), false negative (gray).

	Canz				*Cgus*			
	Chl-a > 1.5 mg/m^3 $b_{bp(\lambda)}$ GMS01 < $b_{bp(\lambda)}$ Morel 1988				$L_{w(\lambda)} < b_{Morel1988}$			
	SeaWiFS		MODIS-Terra		SeaWiFS		MODIS-Terra	
	RT	NB	RT	NB	RT	NB	RT	NB
RT	14/20 (70%)	3/50 (6%)	17/17 (100%)	7/24 (30%)	19/20 (95%)	7/50 (14%)	16/17 (94%)	4/24 (16%)
NB	6/20 (30%)	47/50 (94%)	0/17 (0%)	17/24 (70%)	1/20 (5%)	43/50 (86%)	1/17 (6%)	20/24 (84%)

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