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Long-term evaluation of three satellite ocean color algorithms for identifying harmful algal blooms (*Karenia brevis*) along the west coast of Florida: A matchup assessment

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ABSTRACT

We present a simple algorithm to identify *Karenia brevis* blooms in the Gulf of Mexico along the west coast of Florida in satellite imagery. It is based on an empirical analysis of collocated matchups of satellite and *in situ* measurements. The results of this *Empirical Approach* is compared to those of a *Bio-optical Technique* – taken from the published literature – and the *Operational Method* currently implemented by the NOAA Harmful Algal Bloom Forecasting System for *K. brevis* blooms. These three algorithms are evaluated using a multi-year MODIS data set (from July, 2002 to October, 2006) and a long-term *in situ* database. Matchup pairs, consisting of remotely-sensed ocean color parameters and near-coincident field measurements of *K. brevis* concentration, are used to assess the accuracy of the algorithms. Fair evaluation of the algorithms was only possible in the central west Florida shelf (i.e. between 25.75°N and 28.25°N) during the boreal Summer and Fall months (i.e. July to December) due to the availability of valid cloud-free matchups. Even though the predictive values of the three algorithms are similar, the statistical measure of success in red tide identification (defined as cell counts in excess of 1.5×10^4 cells L^{-1}) varied considerably (sensitivity—*Empirical*: 86%; *Bio-optical*: 77%; *Operational*: 26%), as did their effectiveness in identifying non-bloom cases (specificity—*Empirical*: 53%; *Bio-optical*: 65%; *Operational*: 84%). As the *Operational Method* had an elevated frequency of false-negative cases (i.e. presented low accuracy in detecting known red tides), and because of the considerable overlap between the optical characteristics of the red tide and non-bloom population, only the other two algorithms underwent a procedure for further inspecting possible detection improvements. Both optimized versions of the *Empirical* and *Bio-optical* algorithms performed similarly, being equally specific and sensitive (~70% for both) and showing low levels of uncertainties (i.e. few cases of false-negatives and false-positives: ~30%)—improved positive predictive values (~60%) were also observed along with good negative predictive values (~80%).

1. Introduction

Considerable social and human consequences associated with harmful algal blooms (HABs; or "red tides") have been impacting local food supply and economies throughout history (Mitchell, 2003). Chronic HABs have long caused numerous negative ecological impacts in the Gulf of Mexico (Magaña et al., 2003), especially along the west coast of Florida (Fig. 1). In this region, the toxic marine dinoflagellate, *Karenia brevis*, blooms throughout the year but is mostly observed during the boreal Summer and Fall months (locally referred to as "Florida Red Tide"). It is responsible for water discoloration and fish kills that litter shorelines with tons of dead fish, contributing to the impairment and detrimental degradation of the coastal aesthetics (Van Dolah, 2000).

Besides the localized negative economic impacts that are associated with *K. brevis* blooms (Larkin & Adams, 2007), this organism produces a suite of neurotoxic brevetoxins that bioaccumulate in the food web as they pass to higher trophic levels (Tester et al., 2000). Scavenging seabirds have been found ill, moribund, and are susceptible to death during Florida Red Tide events (Forrester et al., 1977). Widespread die-offs of marine mammals such as manatees and dolphins have been associated with *K. brevis* blooms (Trainer & Baden, 1999).

In addition to environmental damage, blooms of *K. brevis* can also adversely affect public health and welfare in two distinct ways: (1) by ingesting brevetoxin-contaminated shellfish consumers have the risk of acquiring neurotoxic shellfish poisoning (NSP), a temporary but unpleasant illness characterized by gastrointestinal and neurological problems (Poli et al., 2000); and (2) ashore, the inhalation of the odorless aerosolized brevetoxin in the sea spray may cause burning of

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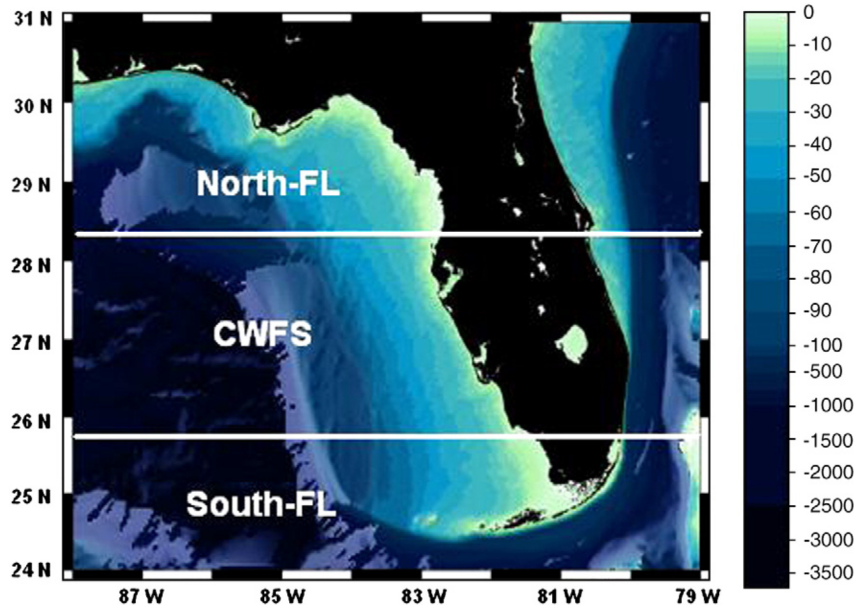

Fig. 1. ETOPO2 bathymetry from the west coast of Florida (units in meters). Horizontal lines indicate sub-regions limits (28.25°N and 25.75°N): North-FL, South-FL and central west Florida shelf (CWFS).

the eyes, induce coughing, sneezing and potentially causing an acute, but fortunately reversible, upper respiratory syndrome (Fleming et al., 2007). Hazardous consequences may also arise by direct contact with brevetoxin, but there have been too few cases to establish the consequences (Kusek et al., 1999). No human fatalities have yet been directly attributed to brevetoxins, but levels of brevetoxin during *K. brevis* blooms can reach levels potentially fatal to humans (Baden et al., 1984; Landsberg, 2002).

An effective and consistent way to accurately identify HABs using space-borne measurements is highly desirable, and an automated surveillance system could provide an economically viable system for documenting the location, magnitude and transport of *K. brevis* blooms (Babin et al., 2005). Indeed, remotely-sensed ocean color efforts have long contributed to the better understanding of the origin, maintenance, and termination mechanisms of the Florida Red Tide (e.g. Mueller, 1979). The ability to track, document and monitor HABs, besides helping to ameliorate local economic impacts, could bring tremendous societal benefits not only to resource and environmental managers, but also to medical health practitioners, the scientific community, coastal inhabitants, and to the tourism and aquaculture industries.

The overall purpose of the current investigation is to couple a remotely-sensed ocean color parameter library with near-coincident *in situ* measurements of the abundance of *K. brevis* to determine the long-term accuracy of three ocean-color algorithms for detecting the Florida Red Tide. This matchup analysis, pairing satellite data with field observations, is used to test the performance of a new HAB-specific algorithm, entitled the *Empirical Approach* (Carvalho, 2008), and those of two other published algorithms: a *Bio-optical Technique* (Cannizzaro, 2004; Cannizzaro et al., 2008) and an *Operational Method* (Stumpf et al., 2003; Tomlinson et al., 2004, 2009).

Here we report for the first time the use of a multi-year data set (from July, 2002 to October, 2006) of measurements of the MODerate Resolution Imaging Spectroradiometer (MODIS; Esaias et al., 1998) to study *K. brevis* blooms along the west coast of Florida. Furthermore, by using the same *in situ* data set for the validation of the satellite indications, the accuracy of the *Empirical Approach* is compared to that of the *Bio-optical* and *Operational* algorithms.

This study is motivated, in part, by attempting to understand if an algorithm (i.e. *Empirical Approach*) based on variables closer to the satellite measurement and less close to the geophysical variables (i.e. primary optical variables; POVs) could be as effective in discriminating between the presence or the absence of *K. brevis* blooms, as those (i.e. *Bio-optical* and *Operational* algorithms) using more highly-derived parameters, as each step of the processing chain is likely to introduce, or amplify, uncertainties in the derived products.

2. HAB-specific algorithms

Throughout this paper the terms “non-bloom” and “non-blooming condition” are used to refer to the absence of the Florida Red Tide, thus accounting for lower concentrations of *K. brevis* cells. However, this could include different concentrations of chlorophyll (Chl): either high-Chl conditions (due to other non-*K. brevis* blooming organisms, such as diatoms) or low-Chl waters.

Details of the three HAB-specific algorithms applied to the satellite imagery are given below.

2.1. Operational method

The high Chl content of *K. brevis* blooms has been suggested to provide means to use satellite Chl anomalies for identifying the Florida Red Tide (Stumpf, 2001; Thomas, 2000). The National Oceanic and Atmospheric Administration's HAB Forecasting System (NOAA-HAB-FS) has implemented a monitoring strategy that exploits the concept of satellite Chl-anomalies (Stumpf et al., 2003; Tomlinson et al., 2004, 2009). Routinely, Chl-anomaly bulletins are issued indicating the possible occurrence of *K. brevis* blooms in the Gulf of Mexico (http://tidesandcurrents.noaa.gov/hab/) using data from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS; McClain et al., 2004). In the current manuscript, this algorithm is referred to as the *Operational Method*.

This algorithm takes into account the difference (i.e. anomaly) between the current satellite Chl image and a background field derived as the running mean of the 60 previous days. At least 10 pixels per bin are required. To avoid mean biases in the presence of slowly changing blooms, a 14-day window is left unused between the analyzed image and those contributing to the generation of the mean. The resolution used for the spatial binning process for generating the Chl mean is 1 km. In the NOAA-HAB-FS implementation of the