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Assessing the impact of the 2014 red tide event on red grouper (*Epinephelus morio*) in the Northeastern Gulf of Mexico

John F. Walter III[1], Skyler R. Sagarese[2], William J. Harford[2], Arnaud Grüss[2], Richard P. Stumpf[3], Mary C. Christman[4]

[1] National Marine Fisheries Service, Southeast Fisheries Science Center, Sustainable Fisheries Division, 75 Virginia Beach Drive, Miami, FL 33149-1099
[2] Cooperative Institute for Marine and Atmospheric Studies, Rosenstiel School of Marine and Atmospheric Science, University of Miami, 4600 Rickenbacker Causeway, Miami, FL, 33149
[3] NOAA National Ocean Service, 1305 East-West Highway, Silver Spring, MD 20910
[4] MCC Statistical Consulting LLC, 2219 NW 23rd Ter. Gainesville, FL 32605

Introduction

Red tide events caused by the dinoflagellate *Karenia brevis* represent key ecosystem stressors that impact regional economics and community dynamics within the Gulf of Mexico (GOM). When severe, red tide blooms can impact local tourism and revenue (Larkin & Adams 2007), and can lead to mass mortalities of marine mammals, increased sea turtle strandings, extensive fish kills, and human illnesses (Landsberg et al. 2009, Flaherty & Landsberg 2011). Although substantial research has focused on the detection of red tide events using satellite derived products (Stumpf et al. 2003, Tomlinson et al. 2009, Hu et al. 2011), considerable uncertainty remains in quantifying the extent and potential ecosystem impacts of a red tide. The Florida Fish and Wildlife Research Institute (FWRI) relies on the detection of *K. brevis* cells to identify a red tide event, even though brevetoxins produced by *K. brevis* can remain a stable source of toxicity in the absence of *K. brevis* cells (Landsberg et al. 2009). This creates the potential for a lag in the natural mortality of affected fauna, which could go undetected if water quality samples do not encounter *K. brevis* cells in large densities (> 100,000 cells per liter) (Stumpf et al. 2008).

In July 2014, the West Florida Shelf experienced severe red tides, which resulted in the death of a large and uncertain number of fish species, including gag grouper (*Mycteroperca microlepis*) and red grouper (*Epinephelus morio*) (http://myfwc.com/research/redtide). These events led the GOM Fishery Management Council's Standing and Ecosystem Scientific and Statistical Committees (SSCs) to postpone recommendations of acceptable biological catch for GOM gag grouper and to request additional analyses from the Southeast Fisheries Science Center (SEFSC) and Florida Fish and Wildlife Conservation Commission (FWC) to model the potential impact of the red tide event on future projections. Field observations from some fishermen cited massive fish kills of commercially important groupers and snappers throughout the Big Bend region which, at the time, were thought to rival the losses experienced during the highly severe 2005 red tide event. Although red tide events are relatively rare in the Big Bend region due to tannin-rich river runoff (Stumpf et al. 2003), 16 red groupers were recovered from this region by the Panama City Laboratory during the 2014 red tide event (Figure 1). The decomposed nature of most fish encountered in the fish kill hindered their ability to identify and recover more specimens (D. DeVries, *pers. comm.*). Moreover, observations during the bottom longline survey between August, 20th 2014 and August, 22nd 2014 did not identify groupers or snappers in surface fish kills (M. Campbell, *unpubl. data*).

Preliminary modeling results by the FWC suggested that the 2014 red tide event was minor in comparison to the 2005 event, based on a combination of fluorescent line height (Hu et al. 2005) and presence of *K. brevis* in water samples (Dave Chagaris, *unpubl. data*), and, therefore, that the 2014 red tide event had a non-significant impact on the natural mortality of gag and red groupers. Consequently, the Gulf of Mexico Fishery Management Council set the acceptable biological catch for gag grouper under the assumption that the 2014 red tide event had no additional effect on the population. Mortality due to baseline levels of red tide may already be included in estimates of natural mortality derived from empirical data (Schirripa & Methot 2013).

A model-based approach has been developed by the SEFSC to alleviate the dependence of red tide detection on human intervention which maps the probability of a red tide event occurring as a function of a suite of satellite derived products across the West Florida Shelf (Walter et al. 2013). The objectives of the present study are to: (1) calculate red tide index values using MODIS (Moderate Resolution Imaging Spectrometer) satellite data for years 2004, 2005, 2007, and 2014; (2) compare MODIS index values to original estimates obtained using Sea-viewing Wide Field-of-view Sensor (SeaWiFS) satellite data for the years where both MODIS and SeaWiFS data are available (2004, 2005, 2007); and (3) provide insights into the severity of the 2014 red tide event on the West Florida Shelf.

Methods

The indices of red tide severity derived previously (Walter et al. 2013) were developed using SeaWiFS satellite sensors which were operational from September 1998 through December 2010. MODIS satellite sensors have been operational since July 2002 and are commonly used to detect and track harmful algal blooms (Hu et al. 2005, Hu et al. 2011). Although both SeaWiFS and MODIS products have been used to detect red tide events (Carvalho et al. 2007), slight differences exist between the two data sources. For example, data loss due to sun glint is more prevalent in MODIS imagery than in SeaWiFS imagery (Tomlinson et al. 2009).

Satellite data

Satellite data were obtained from MODIS Aqua daily imagery for the years 2004, 2005, 2007, and 2014. Satellite imagery was processed onto a 1.1 km grid over the Northeastern Gulf of Mexico as discussed in Walter et al. (2013). Eight derived products potentially considered to be indicative of *K. brevis* blooms were downloaded including:

1. Chlorophyll concentration obtained by the NASA SeaWiFS OC4 algorithm.
2. Chlorophyll anomaly, calculated as the anomaly against a 60 day average chlorophyll value lagged by 15 days (Stumpf et al. 2003, Tomlinson et al. 2004). This measure has been used to identify anomalous phytoplankton levels, and hence likely *K. brevis* blooms, from baseline chlorophyll levels.
3. “Morel,” the backscatter for algae as derived in Morel (1988).
4. “Carder,” the backscatter for algae as derived in Carder et al. (1999).

5. Rrs667, the remote sensing reflectance at 667 nm. The band previously used for SeaWiFS was 670 nm. We are assuming that MODIS Rrs667 is not significantly different from SeaWiFS Rrs670 (Tomlinson et al. 2004).
6. CMbbp, the backscatter ratio of observed backscatter to that expected for marine algae (Tomlinson et al. 2009).
7. ssnLw488, the spectral shape at 488 nm (Wynne et al. 2008). The band previously used for SeaWiFS was 490 nm. We are assuming that MODIS Rrs488 is not significantly different from SeaWiFS Rrs490 (Tomlinson et al. 2004). This product has been observed to distinguish between *K. brevis* blooms and non-*K. brevis* features.
8. "HAB_ensemble," a three-part algorithm that uses chlorophyll anomaly, CMbbp, and ssnLw488 (Tomlinson et al. 2009).

Updating red tide indices using MODIS

Indices of red tide severity were constructed as described in Walter et al. (2013) with the only difference being the source of satellite data used (MODIS vs SeaWiFS). Using the coefficients developed using the SeaWiFS data (Walter et al. 2013), generalized additive models (GAMs) (Hastie & Tibshirani 1990, Wood 2006) predicted the bloom probability in 1.1 km grid cells as a function of remote sensing products derived from MODIS, month, week of year, sea surface temperature (SST), water depth, latitude, and longitude (Walter et al. 2013). Within the original model, the presence/absence of bloom occurrence follows a binomial distribution and is equal to 1 when the algal concentration is greater than 100,000 cells per liter (a threshold generally accepted to represent an active bloom) (Stumpf et al. 2008), and 0 otherwise. The best model given the SeaWiFS data was as follows:

$$\begin{aligned} log\ \frac{\Pr(presence)}{\Pr(absence)} &= as.factor(MONTH) + te(CHL\_ANO, WEEKOFYEAR) \\ &+ te(CARDER, MOREL) + te(SST, WATER\_DEPTH\_M) \\ &+ te(RRS667, WEEKOFYEAR) + te(EASTING1, NORTHING1) \\ &+ te(HAB\_ENSEMBLE, WEEKOFYEAR) + te(WATER\_DEPTH\_M) \end{aligned}$$

The best model predicted the probability of occurrence across the spatial domain of interest, for offshore waters, i.e., waters deeper than 10 meters. It explained 44.2% of the total deviance, had an adjusted coefficient of determination (R^2) of 0.39, and an area under the receiver operating characteristic curve (ROC) of 0.9295. The 5-fold cross-validation overall misclassification rate was 20.9%, with a false positive rate of 22.1% and a false negative rate of 6.2%. This model-based prediction approach mapped the probability of a harmful algal bloom occurring and included associated standard errors obtained using a Monte Carlo approach (Walter et al. 2013).

Four separate indices were calculated including: (1) Depth greater than 10m and 75% minimum convex polygon (10m 75MCP) for the entire year, (2) 10m 75MCP restricted to August through December, (3) Depth greater than 10m and covering critical grouper habitat on the West Florida Shelf (Grouper); and (4) Threshold, where the 10m 75MCP index was 0 or 1, depending upon if the calculated value was above the ROC cutoff for predicting the probability of a bloom (Walter et al. 2013). The cutoff identified for the offshore (>10 m water depth) GAM developed using SeaWiFS satellite data was 0.0785 (Walter et al. 2013). Additional details on model configurations tested, index development, validation, and ROC determination are given in Walter et al. (2013).

Comparison between MODIS and SeaWiFS red tide indices

Index values for all four indices were compared between SeaWiFS and MODIS satellite data to evaluate the similarity in derived indices between data sources for years 2004, 2005, and 2007. The difference between indices as a percentage was calculated using the following equation:

$$\Delta Index_y\,(\%) = \frac{\left(MODIS_y - SeaWiFS_y\right)}{SeaWiFS_y} \times 100$$

where MODIS and SeaWiFS are the respective index values estimated for each year y. Since no SeaWiFS data were available for 2014, only MODIS data were used to produce an index value for this year.

Results

Comparison between MODIS and SeaWiFS red tide indices

The derived index values were relatively similar between satellite data sources, although MODIS estimates tended to produce higher standard errors compared to the SeaWiFS satellite data (Table 1). Relatively large differences in index values were obtained when using the 10m MCP75 index restricted to August through December, with the 2007 index values exhibiting the largest difference (Table 1). This restricted index also produced consistently larger values using SeaWiFS satellite data, whereas no systematic differences between satellite data sources were observed for the 10mMCP75 or Grouper indices (Figure 2). Relative trends in estimated indices were generally similar between satellite data sources, with 2005 exhibiting the largest value among indices and data sources (Figure 3).

2014 red tide event

The 2014 red tide index values for all calculated indices were roughly half the calculated index values for 2005 using the MODIS satellite data (Table 1). The magnitude of the MCP index (0.065) using MODIS satellite data was below the threshold value (0.0785) estimated using the original models and the SeaWiFS satellite data, suggesting that the 2014 red tide event was not severe and was minimal compared to 2005. Overall, the magnitude of the 2014 red tide event appeared similar to the magnitude of the 2004 red tide event (Figure 3). Based on the model-based prediction approach using derived satellite products, the predicted probability of a red tide bloom in 2014 remained relatively high in the Big Bend region from July through November, ranging from 0.2 in July to 0.6 in October (Figure 4). The spatial extent of the 2014 red tide event was also smaller compared to 2005 (Figure 5).

Discussion

The motivation behind the comprehensive model-prediction approach presented here was to provide insights into the potential for red tide presence while alleviating the need for expensive ground-truthed water quality data. The opportunistic and inconsistent spatial and temporal coverage of the FWRI's harmful algal bloom cell count dataset complicates our ability to characterize the extent of observed red tide events. The analysis developed by the FWC used fluorescent line height (FLH) as an indicator of algal blooms (Hu et al. 2005), which requires FWRI cell counts to validate presence of *K. brevis*. Cell counts were then interpolated throughout the WFS to represent the spatial extent of the red tide event, which predicted cell counts in areas not sampled by FWRI. The patchy nature of *K. brevis* blooms raises the question as to whether the FWRI sampling design can adequately track red tide events (Tomlinson et al. 2009). In addition, the relationship between cell counts and toxicity is poorly understood, as high cell counts do not necessarily lead to fish kills. This key issue was recognized by FWC regarding their analysis of red tide mortality of gag and red groupers (D. Chagaris, *pers. comm.*).

The index values produced from MODIS and SeaWiFS satellite data differed slightly, likely due to the random variability in missing data and the presence of clouds which rendered datasets different between data sources. The purpose of this paper was to provide preliminary insights into the 2014 red tide event. Our maps based on a suite of derived satellite products suggest that reliance on water quality samples may have underestimated the spatial and temporal extents of the 2014 red tide bloom. Although both the SEFSC and FWC analyses do not reach the same conclusions regarding the magnitude of the 2014 red tide event, both suggest that it was minor in comparison to the 2005 red tide event.

Current understanding of fish killed by red tide events largely originates from the FWRI fish kill database, which is informed by a statewide fish kill hotline (http://research.myfwc.com/fishkill/). Many of the observations are based on fish that washed ashore following red tide events. Enhanced reporting of red tides, in addition to observations from offshore waters by recreational and commercial fishers, could increase understanding of how red tide events impact offshore species. This could be achieved through the creation of a national program or increased citizen science through outreach educating fishers and other Gulf patrons on their ability to improve fish kill reporting. Further, collections of fish during red tide events would allow for the size/age selectivity of mortality to be determined, and might also allow for some minimum estimates of total mortality.

Additional research is needed to expand analyses to cover additional years and to explore differences in specific satellite products. In particular, potential reasons for the difference between index values for the 10m MCP75 August through December index will be explored to assess whether a bias exists using the MODIS data. The derived indices provide some potential for short-term projections and adaptive management in response to severe red tide events.

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Table 1. Comparison between estimated red tide index values using SeaWiFS and MODIS satellite data sources for select years. Note that analyses were limited to years exhibiting extreme values (2004, 2005, 2007, 2014) due to time constraints, and that threshold values were calculated using the threshold identified for the original generalized additive model built in Walter et al. (2013) using SeaWiFS (0.0785).

Index/Year	SeaWiFS			MODIS			ΔIndex
	Index	SE	Threshold	Index	SE	Threshold	(%)
10m MCP75							
2004	0.049	0.001	0	0.055	0.009	0	11.7
2005	0.148	0.005	1	0.139	0.014	1	-5.9
2007	0.045	0.002	0	0.032	0.007	0	-29.9
2014	-	-	-	0.065	0.010	0	-
10m MCP75 Aug - Dec							
2004	0.117	0.005	-	0.101	0.016	-	-13.3
2005	0.287	0.009	-	0.217	0.023	-	-24.5
2007	0.089	0.002	-	0.048	0.010	-	-45.5
2014	-	-	-	0.110	0.017	-	-
Grouper							
2004	0.033	0.006	-	0.045	0.012	-	36.7
2005	0.087	0.010	-	0.086	0.014	-	-1.7
2007	0.033	0.007	-	0.027	0.010	-	-19.3
2014	-	-	-	0.056	0.013	-	-

Figure 1. Length and age composition of red grouper recovered by the Panama City Laboratory during the 2014 red tide event in the Big Bend region between August, 1st and August, 3rd, 2014. Note that length information was not available for two individuals whose bodies were not intact. Data courtesy of Linda Lombardi and the National Marine Fisheries Service Panama City Laboratory.

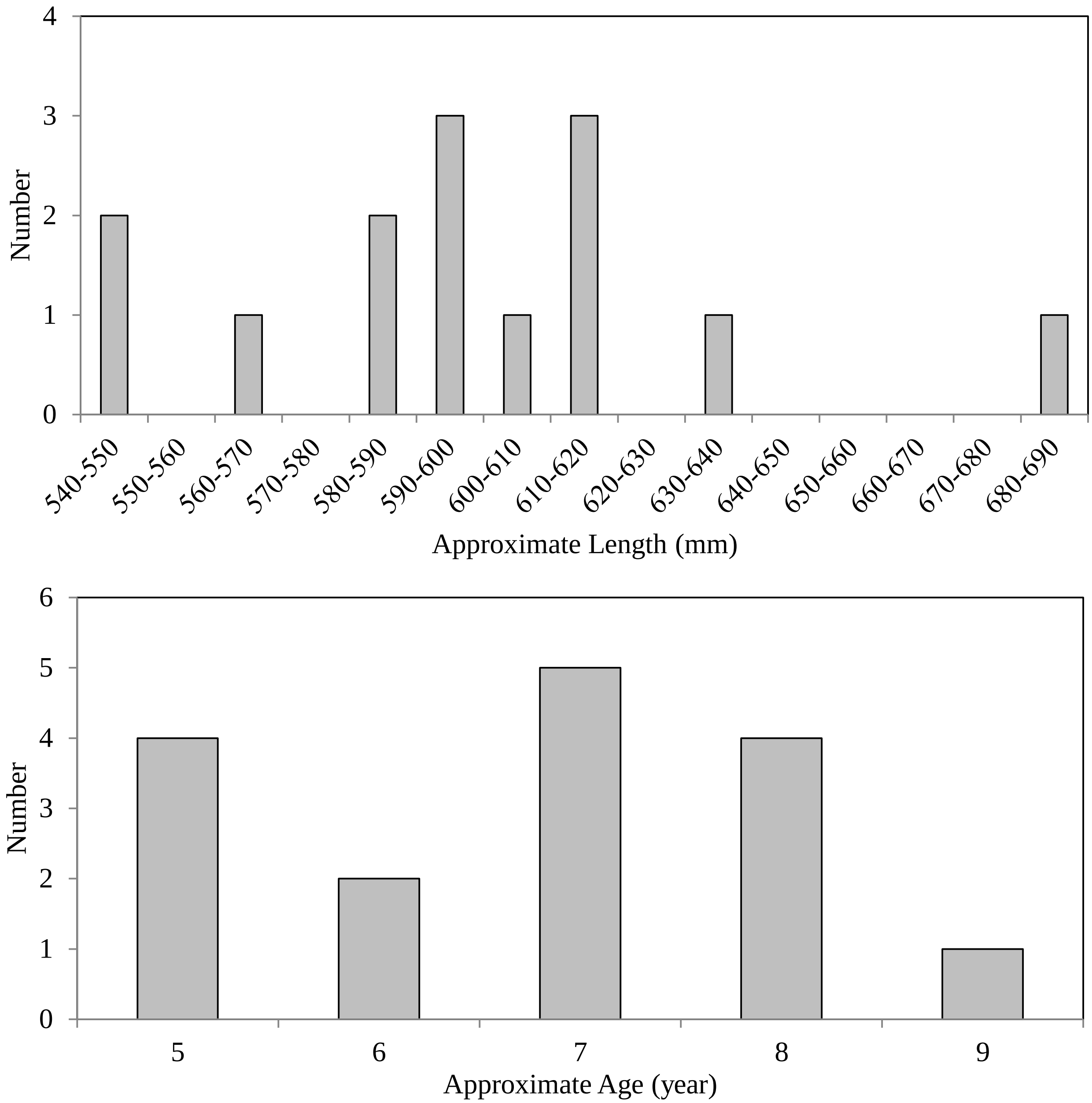

Figure 2. Comparison between estimated red tide index values using SeaWiFS and MODIS satellite data sources. Dashed line reflects a 1:1 line indicating perfect agreement. Note that analyses were limited to years exhibiting extreme values (high: 2005; low: 2007) due to time constraints. Both *x*- and *y*-axes differ between panels.

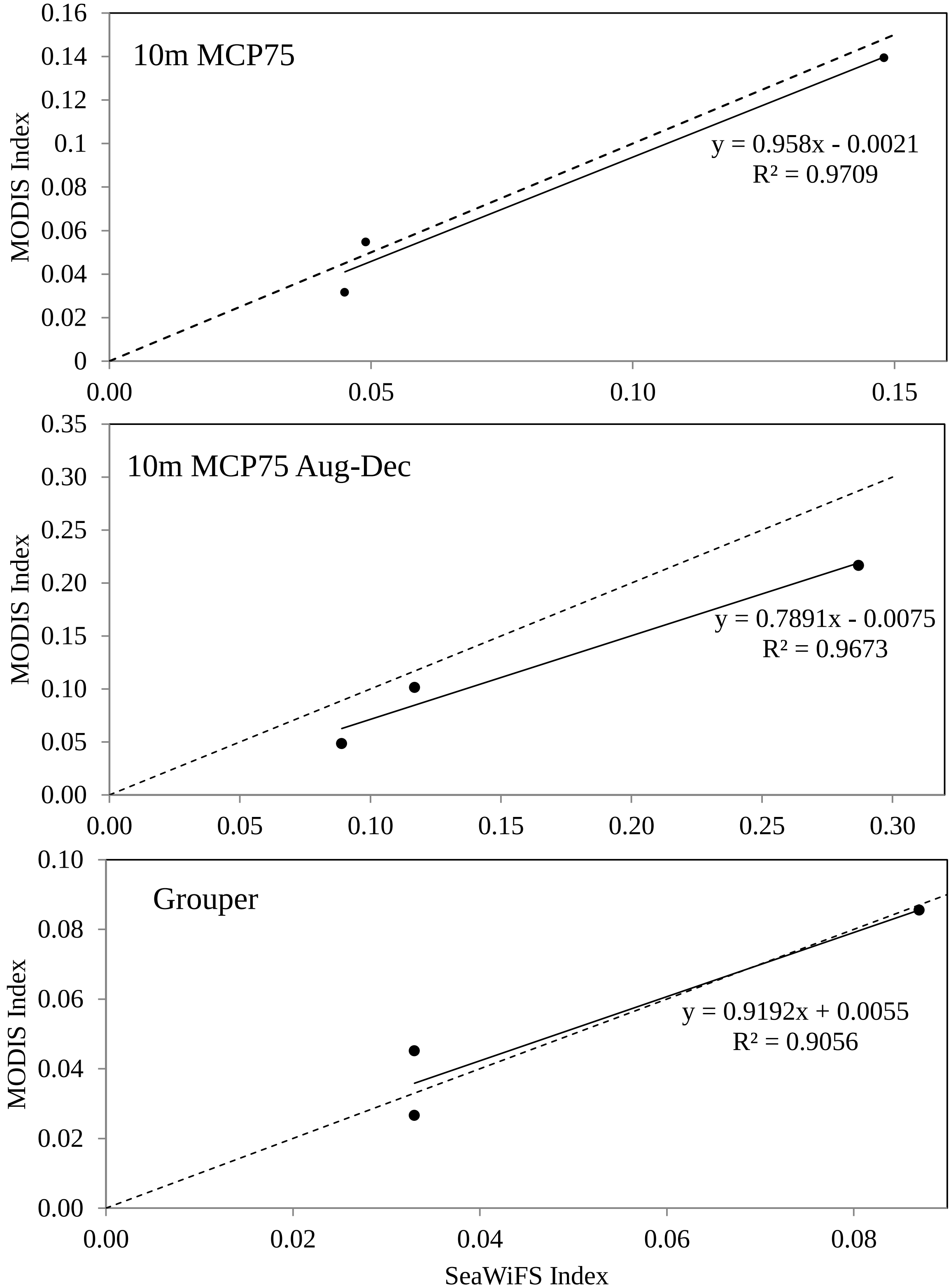

Figure 3. Comparison between red tide index trends using SeaWiFS and MODIS satellite data sources. The dashed line identifies the cutoff value used to separate severe red tide events.

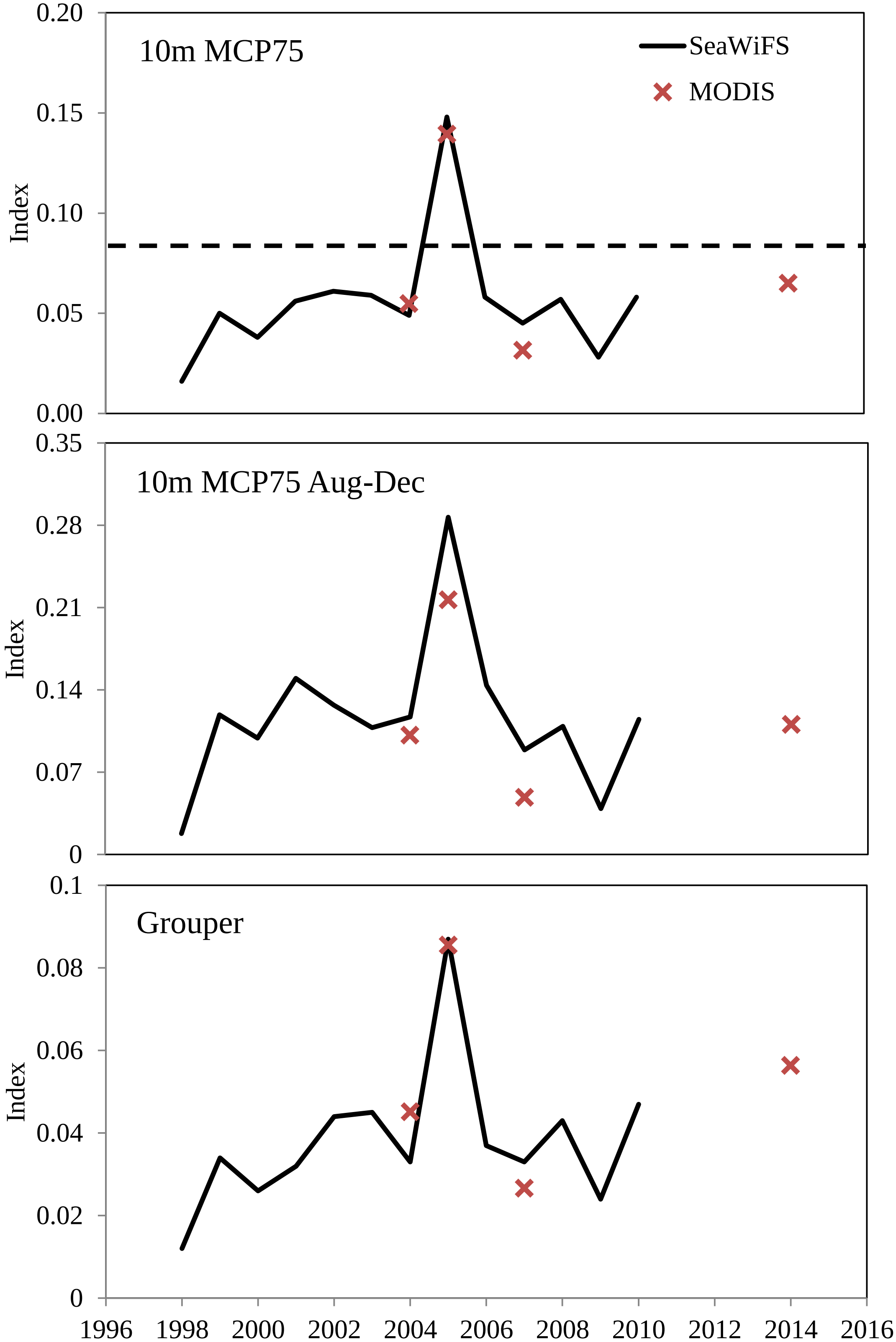

Figure 4. Monthly plots of the predicted probability of a red tide bloom in 2014.

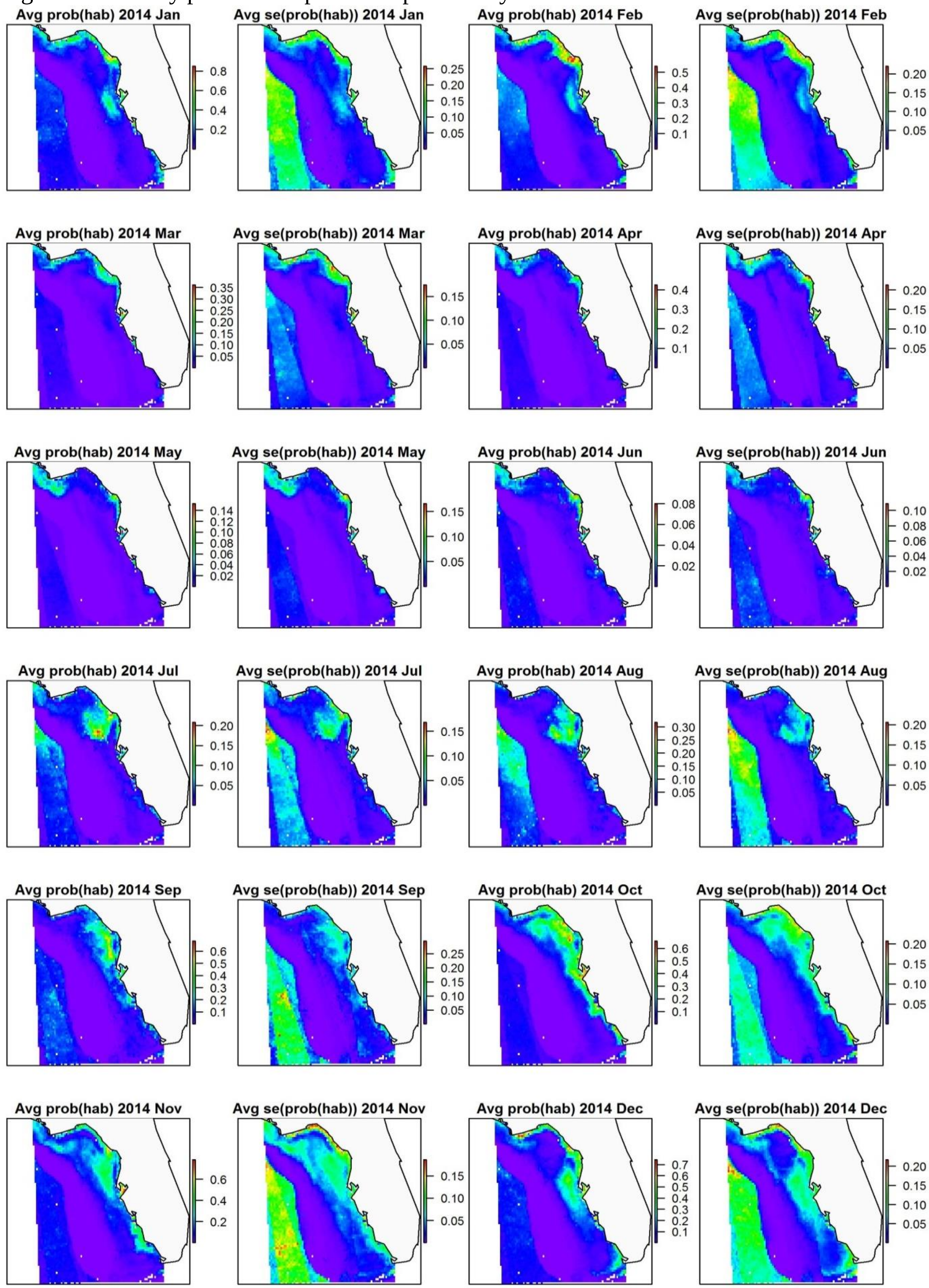

Figure 5. Monthly plots of the predicted probability of a red tide bloom in 2005.