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Article

Satellite-Observed Black Water Events off Southwest Florida: Implications for Coral Reef Health in the Florida Keys National Marine Sanctuary

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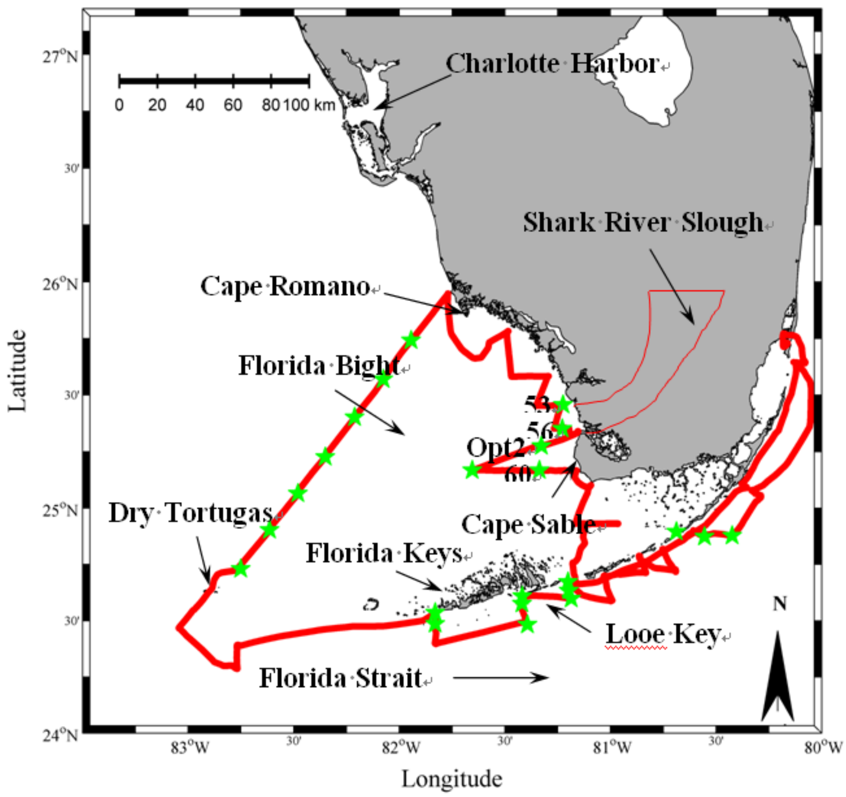
Abstract: A "black water" event, as observed from satellites, occurred off southwest Florida in 2012. Satellite observations suggested that the event started in early January and ended in mid-April 2012. The black water patch formed off central west Florida and advected southward towards Florida Bay and the Florida Keys with the shelf circulation, which was confirmed by satellite-tracked surface drifter trajectories. Compared with a previous black water event in 2002, the 2012 event was weaker in terms of spatial and temporal coverage. An *in situ* survey indicated that the 2012 black water patch contained toxic *K. brevis* and had relatively low CDOM (colored dissolved organic matter) and turbidity but high chlorophyll-a concentrations, while salinity was somewhat high compared with historical values. Further analysis revealed that the 2012 black water was formed by the *K. brevis* bloom initiated off central west Florida in late September 2011, while river runoff, *Trichodesmium* and possibly submarine groundwater discharge also played important roles in its formation. Black water patches can affect benthic coral reef communities by decreasing light availability at the bottom, and enhanced nutrient concentrations from black water patches support massive macroalgae growth that can overgrow coral reefs. It is thus important to continue the integrated observations where satellites provide synoptic and repeated observations of such adverse water quality events.

Keywords: "black water"; MODIS; SeaWiFS; water quality; coral reef; Florida Keys

1. Introduction

The Florida Keys National Marine Sanctuary (FKNMS) is a marine protected area designated in 1990 to protect the coral reef ecosystems adjacent to the Florida Keys (Figure 1). Extensive seagrass beds, mangrove-fringed islands, coral reefs, and more than 6,000 species of marine life within the boundaries of the FKNMS make the area outstanding in terms of conservational, recreational, commercial, ecological, historical, scientific, educational, and aesthetic values [1,2]. The FKNMS is not isolated, but is connected to the deep ocean, the land and the atmosphere through ocean circulation, terrestrial discharge, and atmospheric deposition [3]. The FKNMS is located closely to South Florida, which attracts residents and tourists due to its natural assets.

Figure 1. The thick red line shows the ship track from 27 February to 2 March 2012 and the green pentagrams show the station locations where surface water samples were collected. The region outlined by the thin red lines shows the Shark River Slough.



The increasing population and development in the Florida Keys, together with agriculture and other human activities on the mainland of South Florida, imperil the downstream FKNMS ecosystems. Degradation of water quality around the FKNMS has been a major concern for decades. Between 1991 and 1995, extensive cyanobacterial blooms developed in Florida Bay and the FKNMS in response to increased flows of nitrogen-enriched water from the Everglades Agricultural Area via Shark River Slough [4,5]. A Landsat image (Path 15, Row 43) in late May, 1992, showed the presence of highly discolored and turbid water in western and central Florida Bay, where dense phytoplankton blooms developed in response to nitrogen-enrichment from Shark River Slough [6]. The extensive phytoplankton blooms in Florida Bay led to regional-scale eutrophication in downstream waters of the FKNMS, which included a proliferation of coral diseases and a 38% loss of living coral within the FKNMS [7]. The Comprehensive Everglades Restoration Plan (CERP), a major component of the South Florida Ecosystem Restoration Initiative (SFERI), will be accomplished through a series of projects to modify the freshwater flow to south Florida coastal waters. The operation may further increase nitrogen-rich discharges from Shark River Slough which could further affect the water quality in the vicinity of the FKNMS.

Discolored coastal water off southwest Florida has often been termed as "black water". It refers to dark colored water where the blue light is significantly absorbed by high concentrations of phytoplankton and/or colored dissolved organic matter (CDOM). In January 2002, a black water event was reported off the southwest Florida coast, which lasted through April 2002 [8,9]. The black water between January and April 2002 contained abundant non-toxic (dominated by *Rhizosoliniaceae* diatoms) and toxic (*Karenia brevis*) microscopic phytoplankton. The 2002 event resulted in severe benthic resource decline: 70% of stony coral, 40% of other coral species and almost complete sponge colonies at two reef sites north of Key West, Florida disappeared [10]. Runoff from the Everglades watershed to the southwest Florida Shelf and *K. brevis* blooms, which occurred off Charlotte Harbor (located in the central west of Florida) earlier and migrated to the south along the coast, have been implicated as the causes of the highly publicized black water event in early 2002. Black water has come under scrutiny since then, and several other black water events have been reported [3,11].

Studies using more recent satellite data, which can take precedence over *in situ* surveys and buoy stations in spatial and temporal coverage, have great potential to augment and improve policy making for protecting marine ecosystems [12], e.g., NOAA's existing coral reef decision support systems, including the Integrated Coral Observing Network (ICON)/Coral Reef Early Warning System (CREWS) operated by NOAA's Coral Reef Conservation Program (CRCP).

In early 2012, satellite and *in situ* measurements indicated that another black water event was taking place in southwest Florida coastal waters. Several questions then arose: Was this event stronger or weaker than before? What caused this event?

In this paper, we will focus on the 2012 black water event off the southwest Florida coast (Figure 1) and compare it with the 2002 event. Our main objectives are:

(1) To document the 2012 black water event in southwest Florida coastal waters using Moderate-Resolution Imaging Spectroradiometer (MODIS) measurements, and compare it with the 2002 black water event in the same region but studied with the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) measurements;

(2) To understand what caused the black water event in 2012.

Spectral normalized water-leaving radiance (nL_w) has already been used as an index for determining black water, where low nL_w at 443 nm were observed due to high absorption of phytoplankton and/or CDOM [10]. In this study, we will first delineate the 2012 black water event using satellite-derived nL_w data. Secondly, the 2012 event will be compared with the prolonged 2002 event in terms of spatial and temporal coverage. This is beneficial for environmental change studies, and can provide information on the ecosystem health and variations of the water quality in southwest Florida coastal waters. Thirdly, the potential sources for the black water will be analyzed and discussed. Finally, we will discuss the potential effects of black water on benthic communities.

2. Data and Methods

2.1. In Situ *Survey*

A flow-through system equipped with sensors to measure chlorophyll and CDOM fluorescence, salinity, and turbidity was onboard the R/V *Walton Smith* (WS1202) off south Florida coastal waters from 27 February to 2 March 2012. This was one of the routine bimonthly cruise surveys from the South Florida Program (SFP) of NOAA's Atlantic Oceanographic and Meteorological Laboratory (AOML). The ship track is shown in Figure 1. Water was pumped from about 2.3 m below the surface to a chamber where all parameters were measured after de-bubbling. Data were recorded at 10-second intervals, with spikes and outliers removed using a median filter.

Water samples were collected from the flow-through system to determine chlorophyll-a concentrations and CDOM absorption coefficients using NASA recommended protocols, and then used to calibrate the flow-through chlorophyll and CDOM fluorescence into chlorophyll-a concentrations and CDOM absorption coefficients. The former were converted to phytoplankton pigment absorption using the relationship found in this region [13].

Satellite-tracked drifters were deployed during two AOML-SFP cruises conducted between October and December 2011. The drifters were CODE/Davis style with 1 m surface drogues, with data transmitted to satellites once every 30 min.

2.2. Satellite Data

MODIS and SeaWiFS data at 1 km resolution were downloaded from NASA Goddard Space Center and processed using the most recent updates in calibration and algorithms embedded in the software package SeaDAS (version 6.3). Normalized water leaving radiance (nL_w) at 443 nm, 488 nm and 547 nm was generated. Enhanced RGB (ERGB, R = 547 nm, G = 488 nm, B = 443 nm) images were composited with nL_w at the three wavelengths, following the same approach as in previous studies [10,11]. The use of the 547-nm channel instead of the conventional 670-nm channel as the red band was because $nL_w(670)$ was nearly zero for most waters, therefore yielding much less information than $nL_w(547)$. The ERGB images provide qualitative visualization on various water types: the brownish/reddish color represents high concentrations of phytoplankton, the bright color results from sediment-rich waters or shallow bright bottom, and the darkish color is caused by high concentrations of phytoplankton and/or CDOM. Shallow, seagrass bottom can also cause a darkish color, but the location of such discolored water is static in time and therefore can be easily distinguished from analysis of image time series.

The spectral nL_w data were also used to derive the downwelling diffuse attenuation coefficients at 488 nm based on the QAA algorithm [14] (K_d_488_lee, m^{-1}). A recent validation work showed that the satellite-based K_d_488_lee data were robust, with RMS uncertainties of <15% for the range of 0.03–0.65 m^{-1} in this study region [15].

2.3. River Discharge and Nutrient Concentrations

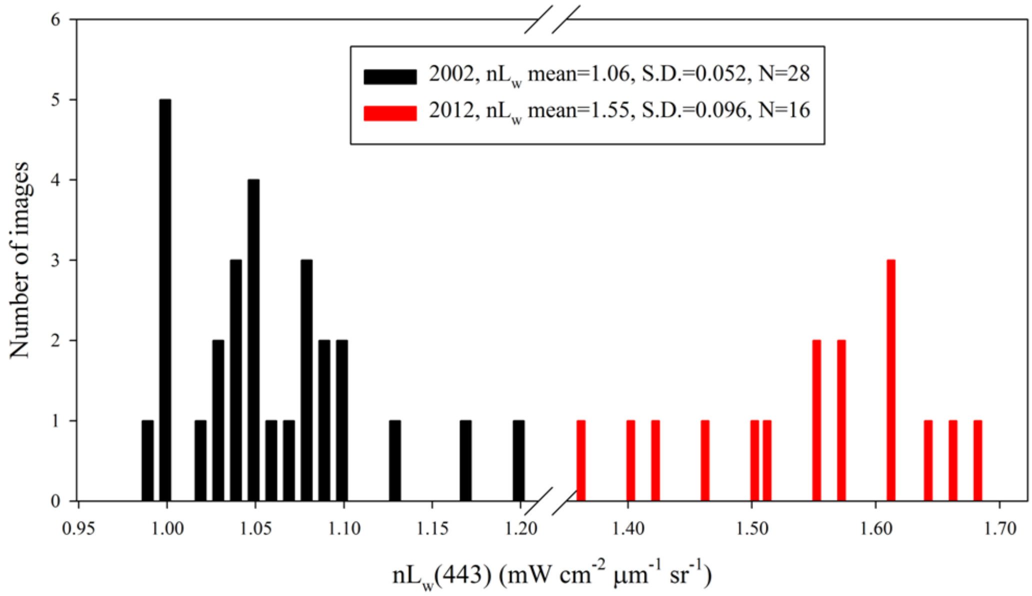
Monthly mean discharge data for Shark River Slough were obtained from South Florida Water Management District for S12_T, as a summation of S12A, S12B, S12C and S12D. Monthly climatology was calculated for the period from 1990 to 2012. Similarly, the annual mean and climatologic discharge data were calculated for 1984–2012.

2.4. Determining nL_w Threshold

In this study, we will delineate the black water coverage using nL_w gradients. As aforementioned, black water patches always show low nL_w values. Thus the threshold for nL_w, below which the region can be referred to as black water, needs to be quantified.

The methods used here are similar to [16]. At first, all ERGB images during the period between January and April of 2002 and 2012 from SeaWiFS and MODIS/Aqua were examined and only those with cloud-free conditions over the black water regions were retained. With this criterion, 29 and 16 images were chosen for SeaWiFS and MODIS/Aqua, respectively. Next a region of interest covering the visually identified black water was outlined manually in ENVI for the chosen ERGB images, where dark colors indicate the black water patches. A gradient image was then generated for each $nL_w(443)$ image corresponding to the outlined ERGB images. For each pixel, the gradient was defined as the difference from adjacent pixels in a 3 × 3 window. A histogram was produced and the mode of the maximum gradient was acquired, which can be efficient to differentiate fronts induced by the black water. Then, a mean value for all pixels in the nL_w image associated with the gradient mode was calculated and used as a threshold. Thus each nL_w image had its own threshold. Finally, all threshold values were pooled together, and the histogram was computed as well as the mean and the standard deviation, as shown in Figure 2. The thresholds for SeaWiFS ranged from 0.99 to 1.2 $mW{\cdot}cm^{-2}{\cdot}\mu m^{-1}{\cdot}sr^{-1}$ for the 2002 black water event and from 1.36 to 1.68 $mW{\cdot}cm^{-2}{\cdot}\mu m^{-1}{\cdot}sr^{-1}$ for MODIS/Aqua for the 2012 black water event. If a universal threshold were to be derived, it would lead to 1.16 and 1.74 $mW{\cdot}cm^{-2}{\cdot}\mu m^{-1}{\cdot}sr^{-1}$ for the two events, respectively, as a result of the average plus two standard deviations. However, in order to calculate the spatial coverage of the black water events more accurately using the gradient method, the image-specific $nL_w(443)$ thresholds were used.

Figure 2. Normalized water-leaving radiance ($nL_w(443)$) thresholds for the 2002 and 2012 black water events during the periods from January to April from SeaWiFS (black bars) and MODIS/Aqua (red bars) cloud-free observations.



3. Results

Figure 3 shows the development and progression of the 2012 black water event. The black water patches are shown by dark color in the ERGB images. In late 2011, a phytoplankton bloom patch, which initiated north of Charlotte Harbor in late September 2011 and was dominated by *K. brevis* as indicated by *in situ* taxonomy data (Figure 3(a–d)), moved southward into the Florida Bight. In early January 2012, the black water patch extended from the region near the coast to the region to the north of the Florida Keys. The patch continued to move southward from late January until early February. At the beginning of February, the black water patch reached the Florida Keys region. From late February to early March the patch retreated slightly toward the southwest coast. In late March, the patch shrank and moved toward the Florida Keys again. The patch nearly disappeared around 12 April. These movement patterns of the black water patch were consistent with the results obtained from satellite-tracked surface drifters deployed between late October and December 2011 in this region (Figure 4). The drifter tracks indicated that the regional flow was generally slow (2.6–7.7 $cm \cdot s^{-1}$) and to the southwest between late October 2011 and early February 2012, and the flow pattern was consistent with the speed and direction of the black water patch observed from satellite images. After early February, the flow moved generally west and then northwest from the beginning of March to late May 2012. This agreed well with the timeline of the dissipation of the black water plume. Furthermore, the flow patterns were in good agreement with previous studies [17]. Water samples collected on 1 and 2 March 2012 showed that the black water patch contained low (between 10^3 and 10^4 $cells \cdot L^{-1}$) to high (between 10^5 and 10^6 $cells \cdot L^{-1}$) concentrations of *K. brevis*, as annotated in Figure 3(i).

Figure 3. Representative MODIS/Aqua enhanced RGB (ERGB) images showing the development and progression of the 2012 black water event, with positions of the black water annotated with arrows. Remote sensing reflectance ($R_{rs} = nL_w/F_o$ where F_o is the extraterrestrial solar irradiance) data from the station (x) in (f) were extracted and shown in Figure 8. Taxonomy data collected on 1–3 November 2011, 21–23 November 2011, 5–7 December 2011, 25–27 December 2011, and 1–2 March 2012 were overlaid in (**a**), (**b**), (**c**), (**d**), and (**i**): N—*K. brevis* not present; P—present < 10^3 cells·L^{-1}; L—low between 10^3 and 10^4 cells·L^{-1}; M—medium between 10^4 and 10^5 cells·L^{-1}; H—high between 10^5 and 10^6 cells·L^{-1}; V—very high > 10^6 cells·L^{-1}.

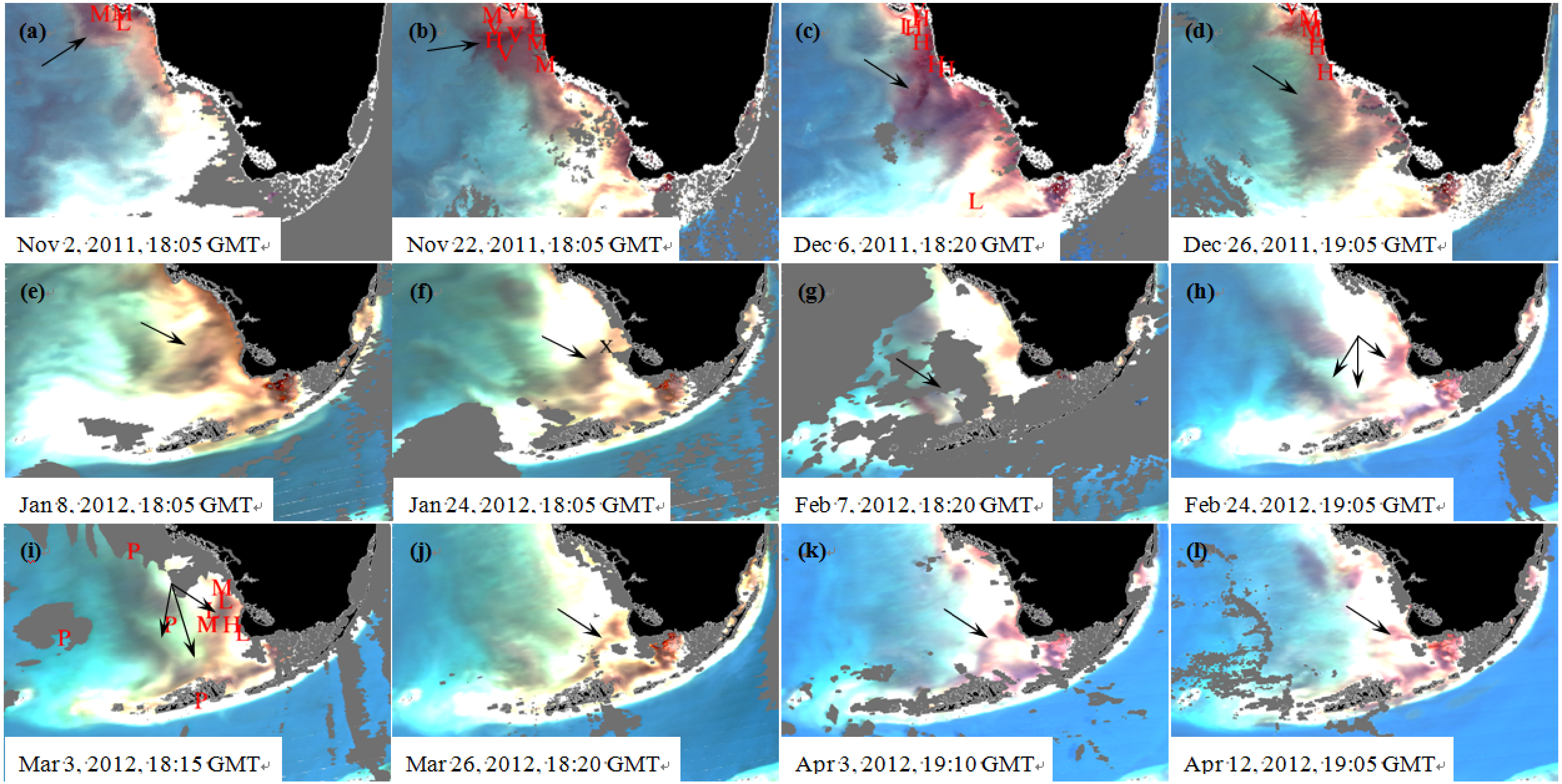


Figure 4. Surface trajectories of drifters released between October and December 2011 during Atlantic Oceanographic and Meteorological Laboratory (AOML)-South Florida Program (SFP) cruises (Figure 1) at Cape Romano and Shark River. The drifters are CODE/Davis style with 1-m surface drogue. Data were transmitted via satellites once every 30 min.

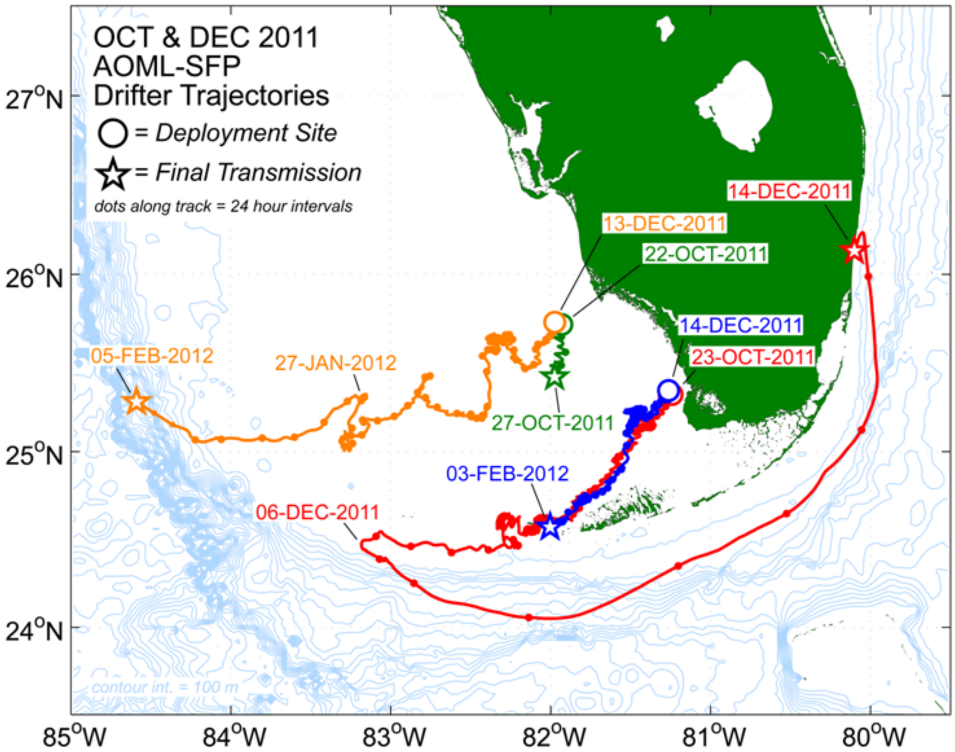
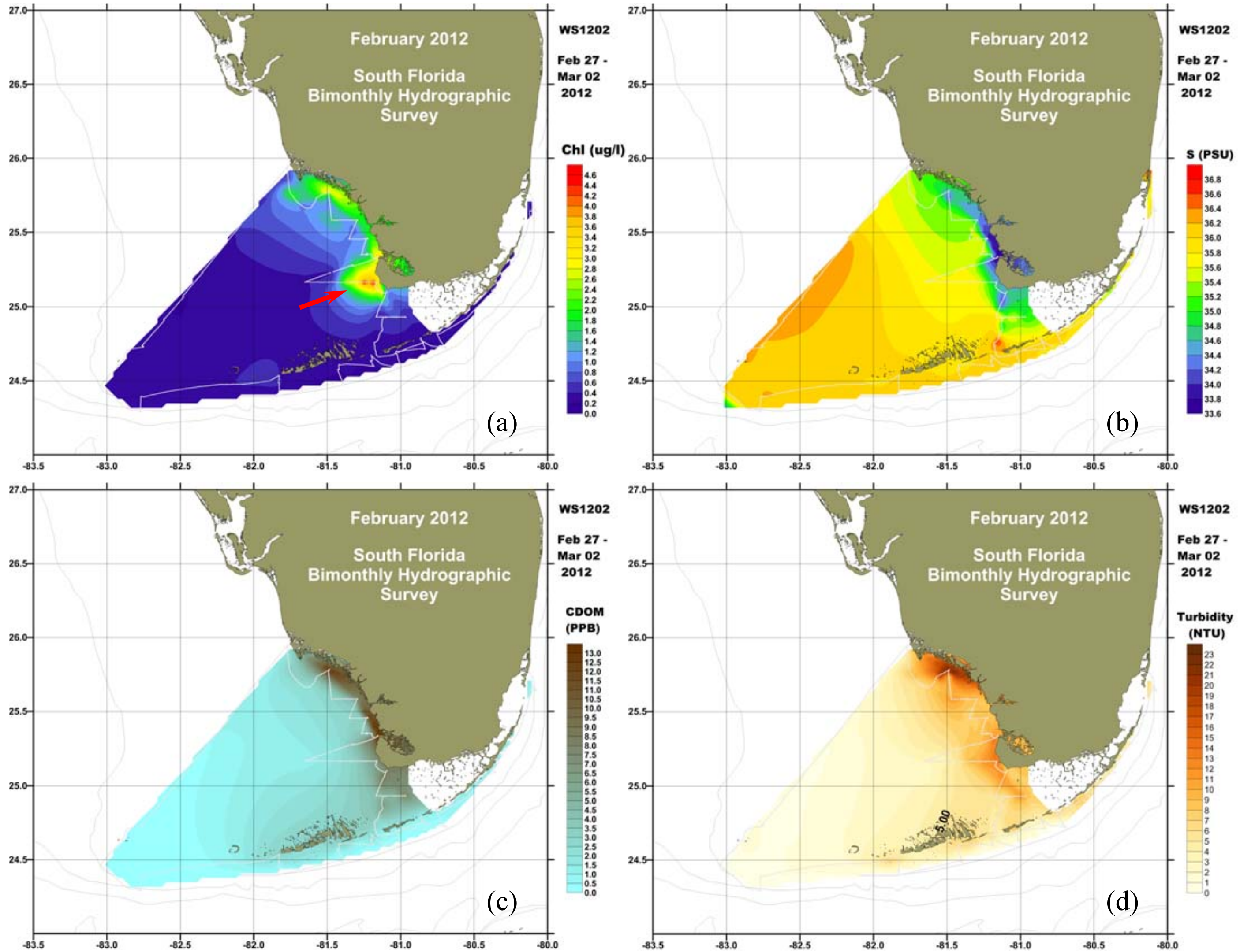


Figure 5 shows surface salinity, chlorophyll and CDOM fluorescence, and turbidity measured by the flow-through system onboard the R/V *Walton Smith*. There was a high chlorophyll patch west of Cape Sable (Figure 5(a)) where CDOM and turbidity were both low. Field measurements also showed high chlorophyll concentrations of 3.6, 4.2, 5.9, and 3.8 mg·m^{-3} for Stations 53, 56, Opt2, and 60 (Figure 1), respectively. Salinity for the high-chlorophyll region was somewhat higher than long-term historical values obtained from the bimonthly routine surveys (http://www.aoml.noaa.gov/phod/sfp/data/ship_obs.php).

Using $nL_w(443)$ as a measure of black water events has followed [10], based on the principle that $nL_w(443)$ will generally decrease with increasing phytoplankton concentration and/or CDOM absorption, as both phytoplankton and CDOM strongly absorb blue light. Figure 6a shows scatter plots of MODIS $nL_w(443)$ against "concurrent" total absorption from phytoplankton pigment ($a_{ph}(443)$, m^{-1}) and CDOM ($a_g(443)$, m^{-1}) from the field measurements. A time window of ±3 h between satellite and field measurements was first tried, with only a few matching pairs found. Then, the time window was relaxed to ±12 h. Results showed a generally decreasing pattern of $nL_w(443)$ with increasing $a_{ph}(443) + a_g(443)$. For $a_{ph}(443) + a_g(443) > 0.3$ m^{-1}, $nL_w(443)$ was generally lower than 2 mW·cm^{-2}·µm^{-1}·sr^{-1}. Yet it is difficult to derive a universal, time-independent $nL_w(443)$ threshold to delineate black water events because each event may contain variable amounts of chlorophyll-a and CDOM, as shown by the different threshold values for the 2002 and 2012 events.

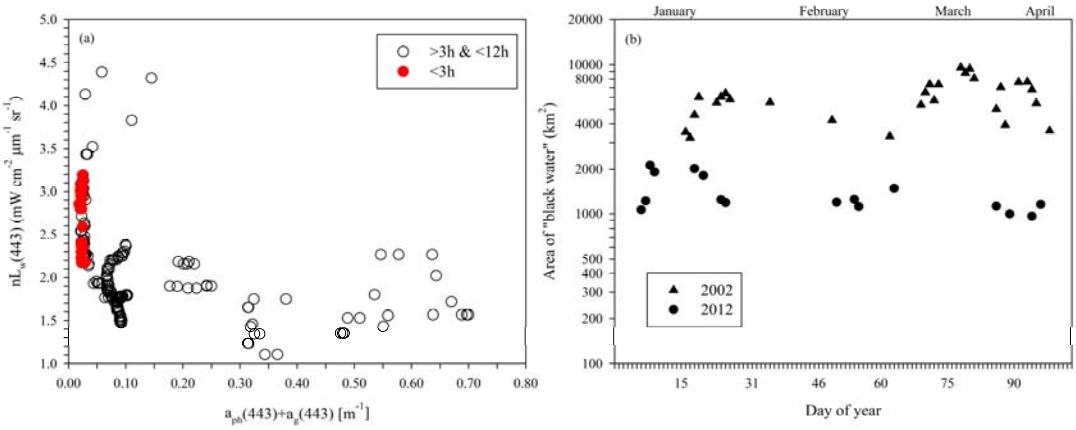
Figure 5. Chlorophyll fluorescence (**a**), salinity (**b**), CDOM fluorescence (**c**), and turbidity (**d**) measured by a flow-through system during a cruise survey from 27 February to 2 March 2012. The white line shows the ship track. The red arrow in (a) shows a patch with high chlorophyll fluorescence. Water samples collected from the patch showed low to high concentrations of *K. brevis* (Figure 3(i)).



Even though the threshold values may change with different black water events, it is still useful to put the 2012 black water event in the context of historical events. The 2002 black water has been reported in detail by [8,9]. The event was first reported in early January 2002, and the black water reached Florida Bight in mid-January. It was retained within the Florida Bight by an anti-cyclonic eddy, and then reached the Dry Tortugas in late March, after which the water was entrained into the Loop Current and advected into the Florida Strait. The 2002 black water event ended around 20 April.

Scatter plots for the spatial coverage of the 2002 and 2012 black water events over time are shown in Figure 6(b). The area of black water ranged from 3,229 km^2 to 9,550 km^2 with a mean of 6,063 (±1,782) km^2 for 2002, compared with from 964 km^2 to 2,123 km^2 with a mean of 1,369 (±379) km^2 for 2012. Although the difference between their temporal coverage was not large, the spatial coverage in 2002 was much larger than in 2012. Generally, in terms of spatial and temporal distributions, the black water event in 2012 was weaker than in 2002.

Figure 6. (**a**) Scatter plot of MODIS/Aqua $nL_w(443)$ against phytoplankton plus CDOM absorption coefficients determined on the same day during the 2012 black water event. (**b**) Comparison between the spatial coverage of the 2002 and 2012 black water events.



4. Discussion

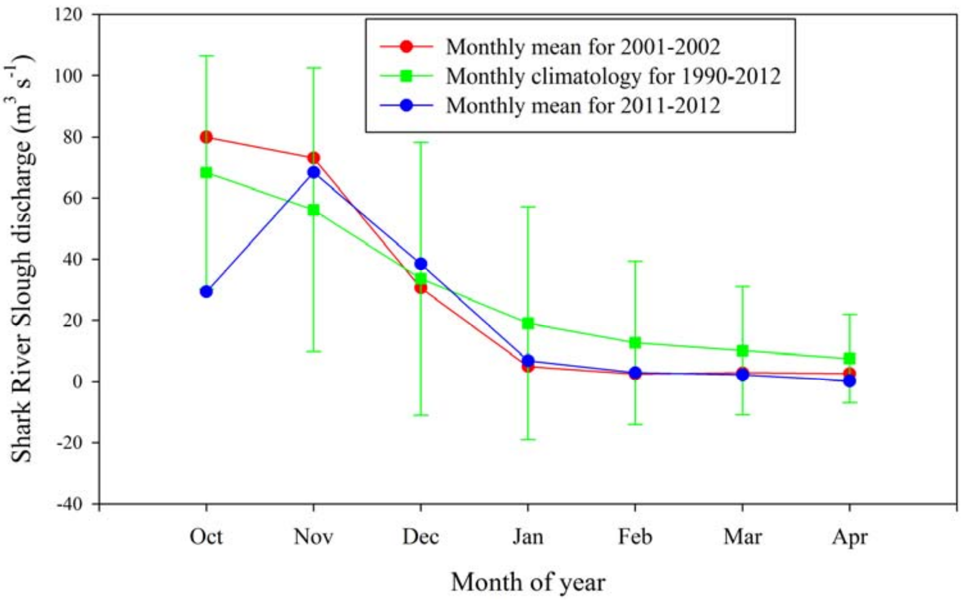
4.1. Causes of the 2012 Black Water Event

A clear understanding of factors that cause black water events and their consequences on the FKNMS ecosystems can improve the efficacy of ecosystem based management strategies. Therefore, the potential sources for the 2012 black water were examined in detail.

As shown in Figure 3, a *K. brevis* bloom patch entered the Florida Bight in late 2011. Therefore, we hypothesize that the 2012 black water patch in the Florida Bight was formed from the red tide bloom that originated earlier off central West Florida and was advected and concentrated by the coastal ocean circulation. Results from *in situ* water samples collected on 1 and 2 March 2012 revealed that the black water in Florida Bight contained *K. brevis* ranging from 333 to 88,000 cells·L^{-1} (Figure 3(i)), which can cause discolored water [18] and supported our hypothesis. The patch also contained abundant non-toxic *Rhizosoliniaceae* diatom.

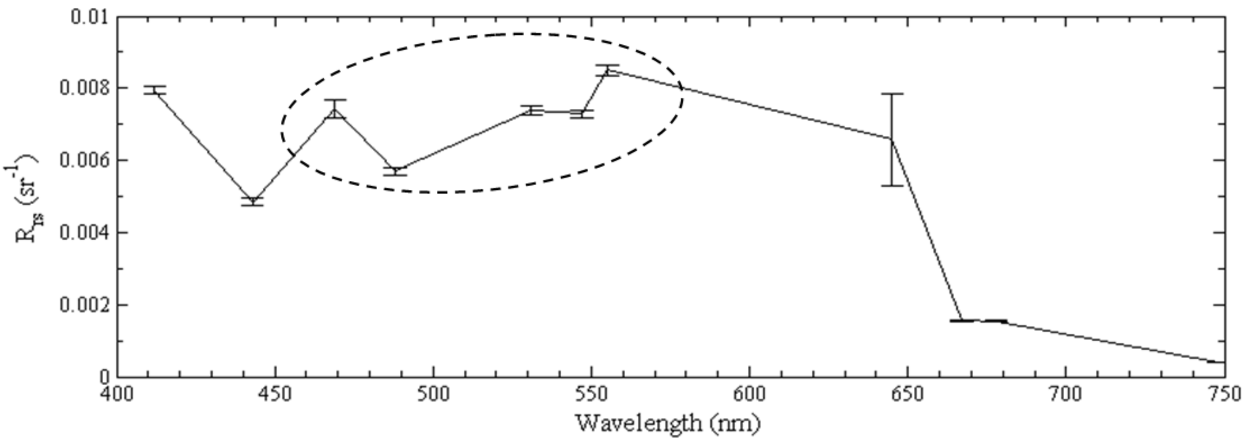
In order to examine the possible effects of river discharge on the black water events, monthly mean discharge of Shark River Slough is shown in Figure 7. The monthly discharges during November 2011 and October–November 2001 were higher than the corresponding monthly climatologies. Although the departures were not statistically significant and the events initiated from earlier *K. brevis* red tide events, these higher-than-usual discharges could have contributed to the evolution of the black water events. Indeed, the linkage between river discharge and algal blooms has been widely recognized in the scientific community. As the river discharge carries "new" nutrients to the coastal ocean, which may add fuel to support and maintain the growth of phytoplankton, the role of river discharge for maintaining the black water and red tide events cannot be ignored [18].

Figure 7. Monthly mean discharges from the Shark River Slough (location shown in Figure 1). Data shown here are the composites of discharge data from S12A, S12B, S12C, and S12D. Data courtesy of South Florida Water Management District.



Although it is generally difficult to differentiate what water constituents are contained in the black water patch by using satellite data alone, Figure 8 shows an exception where the spectral shape of the MODIS R_{rs} could be used to identify the phytoplankton type in the black water patch. The MODIS spectrum was extracted from a location in the black water patch on 24 January 2012 (Figure 3(f)). The spectral curvatures between 469 and 555 nm (*i.e.*, high-low-high-low-high in the R_{rs} spectrum) are unique features for the N-fixing cyanobacterium *Trichodesmium* due to their specific pigment composition [19]. Hu *et al.* [19] used extensive MODIS and *in situ* data to show that such spectral curvatures were only found from *Trichodesmium* blooms and not from other blooms. Therefore, *Trichodesmium* could be an important source of nitrogen required by the black water patch, a phenomenon also noted for sustaining phytoplankton blooms in the Great Barrier Reef lagoon [20]. Also, submarine groundwater discharge in the vicinity of the black water might have provided additional nutrient supplies [7].

Figure 8. MODIS R_{rs} spectrum from 3 × 3 pixels centered at the station marked in Figure 3(f), measured on 24 January 2012 (GMT 18:05). The vertical bars show the standard deviations. The unique spectral curvatures between 469 and 555 nm (high-low-high-low-high, as outlined by the dashed circle) indicates the presence of N-fixation *Trichodesmium*.



4.2. Impacts of Black Water Events on Coral Reef Health

There have been earlier reports about the impacts of black water as mentioned above, such as decline of corals and die-offs of sponge colonies. Here, we give an example of how another black water event affected the benthic habitat. A MODIS fluorescence line height (FLH) image on 19 May 2008 (Figure 9(a)) shows an algal bloom patch at the "Rock Pile" reef (marked with a black cross). This bloom was also associated with a black water event. An *in situ* survey indicated that the bloom was followed by blooms of the chlorophyte *Cladophora liniformis* (Figure 9(b)) on the bottom and over the skeletons of corals, which died in the early 1990's as a result of excessive nutrient loading from Shark River Slough [21]. Figure 9(c) shows the spatial distribution of MODIS K_d_488_lee, which cannot well distinguish the black water patch (as indicated by the high FLH values in the vicinity of the "Rock Pile" reef) from nearby coastal waters because suspended sediments also contribute to K_d_488_lee, making it impractical to delineate black water. However, when combined with bathymetry data, K_d_488_lee could be used to derive the bottom available light (as a percentage of surface light) as exp(−K_d_488_lee × z) where z is the bottom depth. The light available on the bottom in the bloom region was much less than in the nearby non-bloom region (Figure 9(d)). Less light availability has been shown to contribute to the death of corals [22], and the same mechanism could explain the chlorophyte bloom over the skeleton of corals at the "Rock Pile" reef.

Coral reefs are well known to be sensitive to slight increases in nutrient concentrations [20,23] and historical decreases in coral cover in the FKNMS over the past several decades support this precept. Increased flows from Shark River Slough in the early 1990s were linked not only to phytoplankton blooms, but also benthic macroalgal blooms that can overgrow adult corals and inhibit recruitment of juvenile corals (e.g., Figure 9(b)). Figure 10 shows the time series of discharge from Shark River Slough from 1984 to 2011. Between 1991 and 1995, discharges from Shark River Slough increased with parallel increases in nitrogen concentrations, especially ammonium, at Looe Key in the FKNMS [24]. Following this nitrogen enrichment, increased coral disease and die-off reduced coral cover in the

FKNMS to a historical low of 6.4% coral cover between 1996 and 1999 [7]. Accordingly, because both the 2002 and 2012 black water events followed decades of increasing environmental stress and coral loss in the FKNMS, impacts of these subsequent events were relatively minor in terms of coral loss. Although there is relatively little living coral remaining in the FKNMS as compared with historical coverage, it is important to recognize the potential connection between water quality and coral mortality and recovery in the FKNMS. Thus, it is important to continue the satellite and field observations of the water environments of these delicate ecosystems. Such observations not only serve as a direct means to monitor the water environments and anomaly events, but also provide critical information to establish baseline data to assess the long-term changes in the water environments of the delicate coral reef ecosystems, which can help resource managers make ecosystem-based management decisions.

Figure 9. MODIS fluorescence line height (FLH) image (**a**) shows an algal bloom patch at the Rock Pile (marked with a black cross), followed by a bloom of the chlorophyte *Cladophora liniformis* on the bottom and over dead corals (**b**). The corresponding K_d_488_lee map is shown in (**c**). The bottom light availability in percentage, which was calculated from $\exp(-K_d\_488\_lee \times z)$ (z is the bottom depth), is shown in (**d**). The available bottom light in the bloom region is much lower than elsewhere.

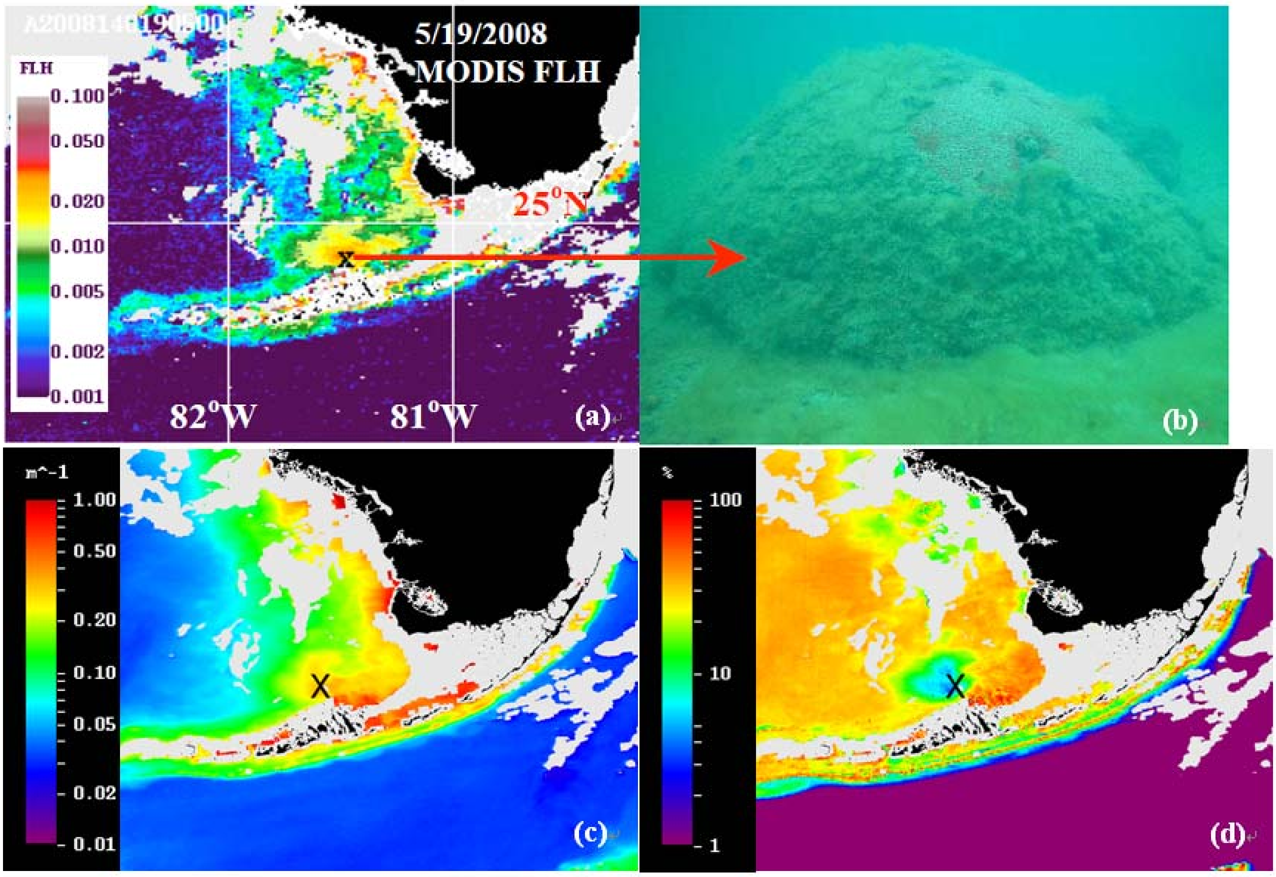
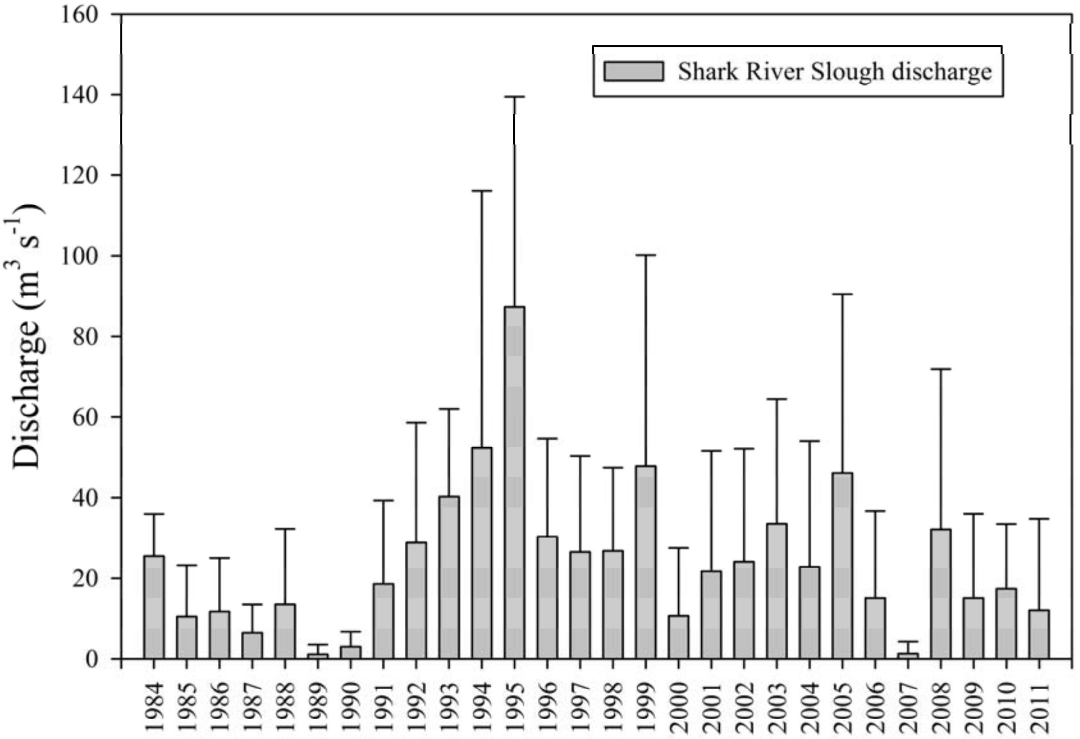


Figure 10. Annual mean discharge of Shark River Slough (summation of stations S12A, S12B, S12C, and S12D) from 1984 to 2011. The standard deviations are also shown. Data courtesy of the South Florida Water Management District.



5. Conclusion

The 2012 black water patch remained in the Florida Bight from early January through mid-April. The patch contained varying concentrations of *K. brevis* that was formed from the *K. brevis* bloom initiated north of Charlotte Harbor in the fall of 2011. Despite similar causes of the event as compared to the 2002 black water event, the black water patch in early 2012 was weaker and much smaller in terms of spatial coverage. The average size of the black water patch is 6,063 (±1,782) km^2 for 2002, compared with 1,369 (±379) km^2 for 2012. However, in general, previous black water patches have negative effects on benthic coral reef communities, such as die-offs of corals and sponge colonies.

The case study here demonstrates the importance of continuous ocean observations by all means, including satellite measurements, *in situ* surveys, and environmental monitoring (e.g., river discharge and nutrient flux). Of these, satellite ocean color observations provide unique information at synoptic time scales to effectively monitor and trace adverse water quality events, from which further insights may be obtained in the understanding of variations in water quality and ecosystem health.

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