Linkages between coastal runoff and the Florida Keys ecosystem: A study of a dark plume event

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[1] Using data collected by satellite sensors, rain and river gauges, and ship surveys, we studied the development and wind-driven transport of a dark water plume from near Charlotte Harbor, Florida, to the Dry Tortugas in the Florida Keys in mid-October 2003. MODIS and SeaWiFS imagery showed that the patch contained an extensive ($\sim$5,500 km^2) phytoplankton bloom that formed originally near the central coast of Florida. The data linked the bloom to high nutrient coastal runoff caused by heavy rainfall in June and August. Total N and P required for the bloom, which may contain some *Karenia brevis* cells, was estimated to be 2.3×10^7 and 1.5×10^6 moles, respectively. The dark color became increasingly dominated by colored dissolved organic matter, toward the Dry Tortugas, where CDOM absorption coefficients (0.08–0.12 m^{-1} at 400 nm) were 2–3 times higher than the surrounding shelf waters, while chlorophyll and inorganic nutrients decreased to negligible levels. *INDEX TERMS:* 4847 Oceanography: Biological and Chemical: Optics; 4857 Oceanography: Biological and Chemical: Pollution; 1640 Global Change: Remote sensing; 4894 Oceanography: Biological and Chemical: Instruments and techniques. **Citation:** Hu, C., F. E. Muller-Karger, G. A. Vargo, M. B. Neely, and E. Johns (2004), Linkages between coastal runoff and the Florida Keys ecosystem: A study of a dark plume event, *Geophys. Res. Lett.*, *31*, L15307, doi:10.1029/2004GL020382.

1. Introduction

[2] Coastal ecosystems are not isolated, but instead are connected to the deep ocean, land, and the atmosphere through various processes including terrestrial discharge, ocean circulation, and atmospheric deposition (“Three Screen Doors” [*Jameson et al.*, 2002]). The southwest Florida coastal system encompasses Gulf of Mexico and Atlantic Ocean waters of the Florida Keys, the Dry Tortugas, and the southwest Florida shelf. The Florida Keys National Marine Sanctuary (FKNMS), one of the nation’s premier marine protected areas, annually attracts 3 million tourists who spend over 1.2 billion dollars [*Causey*, 2002]. The FKNMS is located south and downstream of the Everglades discharge, and of populated areas in South Florida and in the Keys.

[3] Understanding the connections of the Florida Keys ecosystem to nearby or remote regions via coastal and oceanic circulation patterns requires an approach that integrates various observing technologies. With satellite remote sensing, our ability to observe and study the coastal ocean has been significantly enhanced in the past decade. Florida’s “black water” event in early 2002 clearly demonstrated the capabilities of ocean color satellite data to study coastal water quality anomalies [*SWFDOG*, 2002; *Hu et al.*, 2003; *Neely et al.*, 2004]. This anomaly was in part related to fresh water discharged from Southwestern Florida into the ocean. Here we examine another coastal plume event that connected waters from near Charlotte Harbor, Florida (Figure 1) to the Florida Keys in October 2003. We examine satellite, meteorological, and in situ data and discuss the nature and origin of this plume.

2. Data and Methods

[4] Moderate Resolution Imaging Spectroradiometer (MODIS) and Sea-viewing Wide Field-of-View Sensor (SeaWiFS) satellite images were captured and processed in near real-time at the University of South Florida using University of Miami (UM) and standard NASA algorithms. The data contain information on water constituents including phytoplankton abundance (chlorophyll concentration), colored dissolved organic matter (CDOM) content (absorption coefficient), total suspended sediment (TSS) concentration, and bathymetry. Algorithms to de-convolve the individual parameters from the satellite signal are not robust in coastal environments. After removing atmospheric radiance from the image, which is an imperfect process particularly over shallow or very turbid coastal waters, spatial features were clearly identified in the color of the water. Of specific interest were three of the MODIS color bands (551, 490, and 443 nm, Figure 1a) because they clearly trace clear from more turbid water, and the MODIS fluorescence line height data (Figure 1b), which is useful to detect the presence of high phytoplankton concentrations.

[5] Meteorological data were evaluated to understand factors forcing the ocean color features. Specifically, rainfall data collected between 1953 and 2003 at multiple rain gauges for the South Central Florida region were obtained from the National Climatic Data Center, and data were interpolated to compute an average monthly rainfall rate. River discharge data were obtained from river gauges maintained by the US Geological Survey. SeaWinds/QuikSCAT wind scatterometer data were obtained from NASA’s Jet Propulsion Lab (JPL).

[6] *Karenia brevis* (Florida’s red tide species) cell counts were obtained from the Florida Marine Research Institute (FMRI) Harmful Algal Bloom Historical Database. Surface

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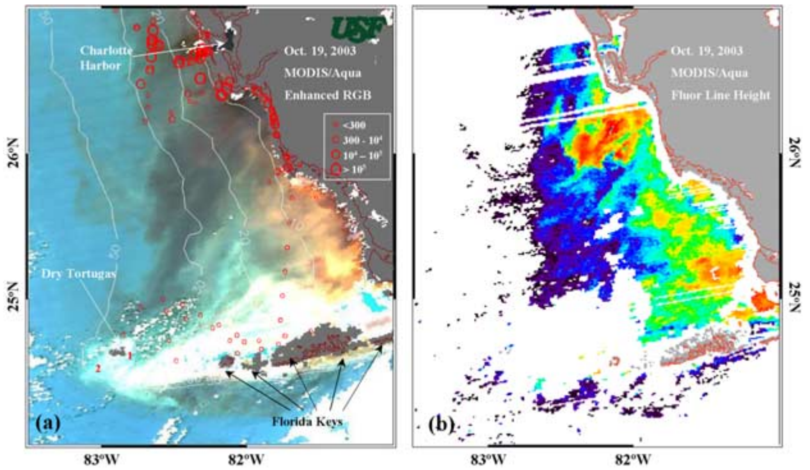

Figure 1. (a) Dark water plume, as revealed in an RGB composite image (R: 551 nm, G: 490 nm, B: 443 nm). The MODIS data were captured on 19 October 2003, 18:20 GMT. Overlaid are bathymetry contours (10 to 50 m) and *K. brevis* concentrations (cells L^{-1}) between 19 September and 19 October 2003. The plume flows across isobaths from the western central Florida coast to the Dry Tortugas. Two water samples ("1" and "2") were collected and analyzed off the Dry Tortugas on 5 and 7 November 2003, respectively; (b) MODIS chlorophyll fluorescence image for the same pass. Fluorescence increases as the color changes from dark blue to green, yellow, and red. Due to sensor artifacts some regions are masked (white color).

salinity distribution was surveyed bi-monthly by the NOAA Atlantic Oceanographic and Meteorological Laboratory (AOML) and UM. Water samples near the Dry Tortugas were collected and analyzed for nutrient contents, phytoplankton species, cell counts, and CDOM absorption coefficient. Nutrient concentration was determined on a Technicon Autoanalyzer II using the World Ocean Circulation Experiment (WOCE) guidelines.

3. Results and Discussion

[7] MODIS imagery in Figure 1a (19 October 2003) shows a plume of dark coastal water originating near and around Charlotte Harbor on the western coast of central Florida and extending to the Dry Tortugas. Overlaid on the image are bathymetry contours (10 to 50 m) and *K. brevis* concentrations between 19 September and 19 October 2003. Subsequent imagery shows that upon flowing past the Dry Tortugas, the plume turned to the southeast and was entrained around the Tortugas Eddy [*Fratantoni et al.*, 1998], before meandering back toward the Florida Keys.

3.1. Nature of the Plume

[8] Distinguishing phytoplankton from CDOM using ocean color data is difficult in the complex coastal environment. Several bio-optical algorithms have been developed, but results are not fully satisfactory. MODIS addresses this problem in part using a unique spectral band designed to quantify chlorophyll fluorescence in the red part of the spectrum. The chlorophyll fluorescence line height (FLH) image (Figure 1b) shows that there is a phytoplankton bloom in the immediate vicinity of Charlotte Harbor, and that phytoplankton concentrations decrease as the water disperses offshore to the southwest. At about 25.5°N, 82.7°W the fluorescence signal appears to be the same as that of the surrounding clear water. This is evidence that the cause for the dark color (strong absorption in all wavelengths) changes downstream in the plume. Nearshore it is derived from high concentrations of phytoplankton and CDOM, but farther downstream the dark color is caused primarily by CDOM.

[9] Analysis of phytoplankton abundance in field samples supports this conclusion. Near Charlotte Harbor phytoplankton concentration was high and even contained some numbers (10^4–10^5 cells L^{-1}) of *K. brevis*. However, two samples collected in the dark plume near the Dry Tortugas in early November 2003 contained few phytoplankton cells, while CDOM absorption coefficients at 400 nm were 0.124 and 0.082 m^{-1}, respectively. These are two to three times higher than those of the surrounding clear waters (~0.04 m^{-1}).

[10] A simple nutrient budget helps understand how much nutrient is required to develop a bloom like the one observed here. Using the MODIS FLH data to estimate the surface area of the bloom and using SeaWiFS-derived chlorophyll data (a factor of 0.5 is applied for CDOM-rich waters), we estimated that at least 5500 image pixels (about 1 km^2/pixel) were associated with elevated chlorophyll values (0.5 to 3 mg m^{-3}). Assuming the background chlorophyll concentration is 0.2 to 0.5 mg m^{-3} from offshore to nearshore waters, and that the bloom layer is 5 m deep, the excess chlorophyll in the plume amounts to 27×10^6 g Chlorophyll. This would require about 46 ton (46×10^6 g) of total phosphorus, if a 1.7:1 (weight:weight) ratio is used between phosphorus and chlorophyll [*Vargo et al.*, 2004]. Further, assuming a redfield N:P ratio of 7:1 (weight:weight), the bloom required about 322 ton (2.3×10^7 mol) of N. Dividing by the estimated volume of the plume, this would yield an average concentration of ~0.056 μM phosphorus and ~0.83 μM nitrogen in the plume, with higher values near central Florida and decreasing concentrations near the Dry Tortugas. Indeed, in the two samples collected from the dark water near the Dry Tortugas (Figure 1), nitrite was 0.01–0.02 μM, nitrate was 0.05–0.09 μM, silicate was 1.4–3.65 μM, ammonia was 0.16–0.31 μM, and phosphate was 0.08–0.1 μM. The lower

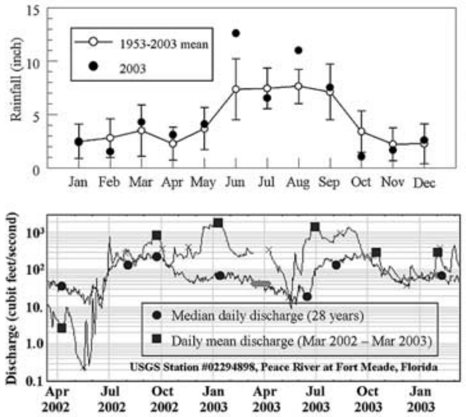

Figure 2. Top: Average monthly rainfall (inches) for the south central Florida area (data courtesy of the National Climatic Data Center); Bottom: river discharge data showing significantly higher than normal river flow between June and September 2003 (data courtesy of the US Geological Survey).

concentrations were likely due to uptake by phytoplankton. Because of these low concentrations, the plume did not stimulate phytoplankton growth near the Dry Tortugas.

[11] The plume is an example of a mechanism that connects the land with somewhat remote ocean environments. The plume provides a potential conduit for cells and larvae, as well as pollutants, pathogens, or even harmful algae cells. It has been suggested that *Serratia marcescens*, a common bacterium found in humans, contributed substantially to the coral die-offs in the Florida Keys in the 1990's [*Patterson et al.*, 2002], but the actual source of these pathogens remains obscure. Clearly, the plumes may also have other effects, such as protection against incident UV due to elevated CDOM levels [*Williams*, 2002].

3.2. Cause of the Plume

[12] Weather records show that June and August 2003 had a positive rain anomaly of 4–7 inches in excess of a 51-year climatology. River stage height in local rivers also showed that discharges increased sharply during this time and in subsequent months. Large rivers that discharge into Charlotte Harbor, such as the Peace and Caloosahatchee Rivers, experienced a 5–10 fold higher discharge rate between June and September 2003 relative to a 28-year climatology (Figure 2). Nutrient concentrations in the rivers were also several times higher than normal during these rainfall periods according to the Southwest Florida Water Management District.

[13] MODIS and SeaWiFS images revealed that coastal waters near Charlotte Harbor were relatively clear in May and early June 2003, presumably because of low riverine discharge during that time. After 25 June 2003, several dark water patches appeared near estuaries and rapidly joined to form a narrow band (~15-km wide) along the coast. The satellite data shows that this coastal plume originated in estuaries, which therefore physically linked the plume to the heavy rains of summer 2003 and subsequent high riverine discharges (Figure 2).

[14] The spatial distribution of the dark water patches did not change through mid-August 2003. At that point, the plume separated from the coast and started to disperse to the west. By 9 September 2003, the dark patches were approximately 40-km wide off Charlotte Harbor. By 19 September 2003, a large dark water patch had formed, covering ~4700 km^2 west and southwest of Charlotte Harbor. This patch remained stagnant for about a month.

[15] A series of surveys conducted in June–October 2003 confirmed the large amount of fresh water aggregating off Florida during this period. Figure 3 shows dark water patches immediately off Charlotte Harbor in early October 2003, when a band of low salinity water was found along the entire southwest Florida coast. Earlier salinity surveys showed similar low salinity patches. Compared with similar periods in 2002 (data not shown), these low salinity waters clearly indicate coastal runoff due to high rainfall. Low salinities were found near the Everglades rivers (Figure 3b), but the MODIS image is not very dark due to high backscattering of suspended sediments and shallow bottom.

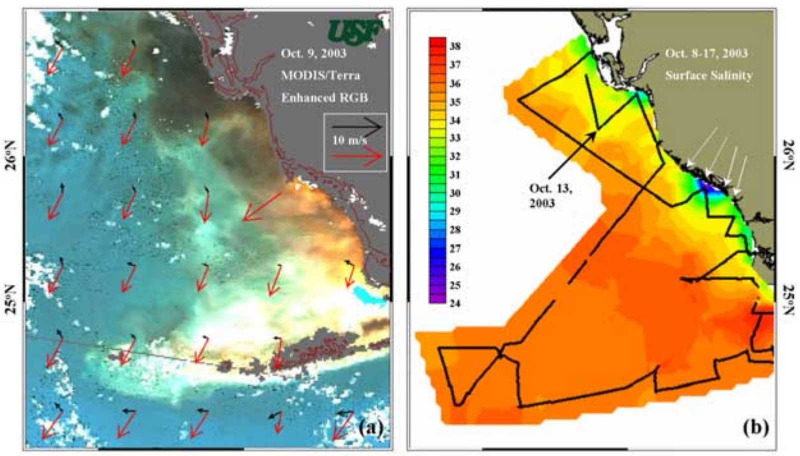

Figure 3. (a) MODIS RGB image on 9 October 2003 shows dark water patches near Charlotte Harbor. Arrows show average wind speed and direction (day and night) for 8–14 October (black) and 15–19 October 2003 (red), obtained from the QuikScat scatterometer (data courtesy of NASA JPL); (b) Low salinity patches for the same region from AOML/UM ship surveys. Black lines indicate cruise tracks, and white arrows indicate approximate locations of the Everglades rivers.

[16] On 15 October, during a period of low rainfall over adjacent land, the plume drifted to the southwest, forming the pattern captured in Figure 1. During this process, several other dark water patches formed near Naples and the Ten Thousand Islands area. These patches eventually dissipated or joined the large patch drifting to the southwest.

[17] The water off central Florida was effectively stagnant between June and mid-October. Wind data from QuikScat did not show any synoptic long-lasting patterns during this period. Weak wind events did not last more than two days (Figure 3a). In contrast, mean wind speed between 15 and 19 October 2003 was >5 m/s towards the southwest. We believe this is the primary forcing that led to the offshore dispersal of the plume. Note that the plume dispersed across isobaths, in a direction slightly more to the southwest than the wind itself.

[18] The plume spread slowly through 21 November 2003, until a strong wind event likely led to strong vertical mixing and sediment resuspension in nearshore shallow waters, factors which then masked the color signal. During this entire period through late November, dark water patches were continuously observed near the Dry Tortugas and the Florida Keys, as the patch dispersed and was entrained in local currents along the Florida Keys, including the Tortugas eddy.

4. Conclusion

[19] Using satellite data from MODIS, SeaWiFS, and QuikScat sensors, as well as ground-based observations including rainfall, river discharge, salinity surveys, and analyses of phytoplankton and nutrient concentrations and CDOM absorption, we studied a dark water plume that occurred off southwest central Florida in October 2003. The low-salinity coastal runoff plume, caused by heavy rainfall during the June and August 2003, originated around Charlotte Harbor and moved offshore to the Dry Tortugas due to strong winds in October 2003.

[20] The upstream portion of the dark water plume contained an extensive phytoplankton bloom (which may contain some *K. brevis* cells), as revealed by MODIS fluorescence imagery. Downstream, the bloom diminished and *K. brevis* were below count detection, so that near the Dry Tortugas high CDOM content dominated the color of the water. The MODIS fluorescence data provided a valuable tool to confirm the extent of the phytoplankton bloom in coastal waters where ocean color data are otherwise hard to interpret.

[21] Based on SeaWiFS data and a simple nutrient budget model, we estimated that to support this extensive bloom more than 2.3×10^7 mol N and 1.5×10^6 mol total phosphorus would be needed. Sufficient quantities of nutrients were supplied by local rivers to sustain the bloom. In late October and November, CDOM and nutrients may be supplied by both coastal runoff and upwelling. However, past cruise surveys from AOML/UM indicated that coastal shallow water in this region tends to be well mixed fall, and therefore upwelling should not change its color or temperature.

[22] The motion of the plume suggests that land runoff can reach remote coral environments in the FKNMS, which is connected with other south Florida coastal ecosystems through various transport processes [*Lee et al.*, 2002]. Remote sensing provides unique data to document and study the nature and cause of such transports, which link the coastal ecosystem on the Southwest Florida Shelf, including the estuary and local rivers, to the Florida Keys two hundred kilometers away. This study highlights the need for a synoptic observing system that is capable of addressing the connection between land and remote ocean environments.

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References

Causey, B. D. (2002), The role of the Florida Keys National Marine Sanctuary in the South Florida Ecosystem Restoration Initiative, in *The Everglades, Florida Bay, and Coral Reefs of the Florida Keys, An Ecosystem Source Book*, edited by J. W. Porter and K. G. Porter, pp. 883–894, CRC Press, Boca Raton, Fla.

Fratantoni, P. S., T. N. Lee, G. P. Podesta, and F. Muller-Karger (1998), The influence of Loop Current variability on the formation and evolution of cyclonic eddies in the Southern Straits of Florida, *J. Geophys. Res.*, *103*, 24,759–24,779.

Hu, C., K. E. Hackett, M. K. Callahan, S. Andréfouët, J. L. Wheaton, J. W. Porter, and F. E. Muller-Karger (2003), The 2002 ocean color anomaly in the Florida Bight: A cause of local coral reef decline?, *Geophys. Res. Lett.*, *30*(3), 1151, doi:10.1029/2002GL016479.

Jameson, S. C., M. H. Tupper, and J. M. Ridley (2002), The three screen door: Can marine "protected" areas be effective?, *Mar. Pollut. Bull.*, *44*, 1177–1183.

Lee, T. N., E. Johns, D. Wilson, E. Williams, and N. Smith (2002), Transport processes linking south Florida coastal ecosystems, in *The Everglades, Florida Bay, and Coral Reefs of the Florida Keys, An Ecosystem Source Book*, edited by J. W. Porter and K. G. Porter, pp. 309–342, CRC Press, Boca Raton, Fla.

Neely, M. B., et al. (2004), Florida's black water event, in *Harmful Algae 2002: Proceedings of the Xth International Conference on Harmful Algae*, edited by K. A. Steidinger et al., Fla. Inst. of Oceanogr., St. Petersburg, Fla., in press.

Patterson, K. L., J. W. Porter, K. B. Ritchie, S. W. Polson, E. Mueller, E. C. Peters, D. L. Santavy, and G. W. Smith (2002), The etiology of white pox, a lethal disease of the Caribbean elkhorn coral, *Acropora palmate*, *Proc. Natl. Acad. Sci. U. S. A.*, *99*, 8725–8730.

SWFDOG (2002), Satellite images track "black water" event off Florida coast, *EOS Trans. AGU*, *83*, 281 and 285.

Vargo, G. A., et al. (2004), Four Karenia brevis blooms: A comparative analysis, in *Harmful Algae 2002: Proceedings of the Xth International Conference on Harmful Algae*, edited by K. A. Steidinger et al., Fla. Inst. of Oceanogr., St. Petersburg, Fla., in press.

Williams, D. E. (2002), Population ecology of bleaching-stressed *Amphistegina gibbosa* in the Florida Keys (1991–1999): Influence of the solar radiation on reef-dwelling foraminifera, Ph.D. dissertation, Univ. of S. Fla., Tampa.

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