University of South Florida

USF

Final report

20 July – 31 December 2003

Satellite monitoring of the FDEP Gulf dispersal of the Piney Point treated wastewater

Chuanmin Hu and Frank E. Muller-Karger

Institute for Marine Remote Sensing (IMaRS)

http://imars.usf.edu/

Phone: (727) 553-3987; Fax: (727) 553-1103

Email: hu@seas.marine.usf.edu

College of Marine Science, St. Petersburg Campus

University of South Florida • 140 Seventh Avenue South • St. Petersburg, Florida 33701-5016

(727) 553-1528 • Fax:(727) 553-1189

Final Report: 20 July – 31 December 2003

Satellite monitoring of the FDEP Gulf dispersal of the Piney Point treated wastewater

Table of Contents

Summary

Operational and research satellite sensors such as MODIS, SeaWiFS, and AVHRR provide a unique means to monitor the surface ocean. Observations from these satellites were used to monitor the offshore dispersal of treated Piney Point wastewater. The dispersal was conducted during 35 barge trips from 20 July to 30 November 2003 in an offshore region in the Gulf of Mexico. About 248 million gallons of wastewater were discharged over this period. The satellite observations complemented field samples, surface float trajectories, and model results. Satellite data provided real-time and accurate information on the position of the Loop Current, a strong oceanic current that carried materials away from the dispersal region and into an oceanic regime. The satellite data were instrumental to outline the area where the barge would operate prior to the initiation of the dispersal. In addition, the weekly synoptic satellite data analysis helped understand the motion of offshore waters and the way dispersed waters likely moved.

Our ***primary*** objective was to document surface circulation patterns, changes in surface ocean color that may have implied changes in the concentration of chlorophyll, and help determine possible movement of undiluted discharge toward near-shore environments. We examined areas on the West Florida Shelf (including the downstream area) and near the Florida Keys, and compared observations to spatial and temporal patterns in chlorophyll measured in 2003 with satellite images collected over the previous seven years. This baseline analysis helped understand any possible changes associated with the dispersal of Piney Point wastewater.

The satellite data allows precise measurements of the concentration of colored dissolved organic matter (CDOM, a chemical indicator of terrestrial or river influence) and chlorophyll (a biological indicator of local phytoplankton growth) in surface ocean waters. The results showed that there were no anomalous variations in either CDOM or chlorophyll on the West Florida Shelf or waters near the Florida Keys relative to those seen in the past seven years. During 2003, there was no change in either CDOM or chlorophyll concentration relative to previous years between July and October. In November and December 2003, CDOM increased slightly (20-30% compared to previous months) in some areas of the West Florida Shelf but in areas disconnected from the Piney Point discharge region as confirmed by surface drifter data. Chlorophyll concentration remained effectively unchanged over the discharge period. Chlorophyll remained within the normal range (on average, below 0.2 mg m^{-3} for all deep water areas and below 0.5-0.6 mg m^{-3} for near shore waters off the central Florida coast). There was no evidence of enhanced biological activity near or downstream of the discharge area.

We examined imagery daily. We enhanced the color imagery and used the highest resolution provided by the sensors. We found that river waters from the northeastern Gulf of Mexico led to much larger changes in the color of the water than the Piney Point discharges even in the discharge region. A few images collected after mid-October 2003 provided exceptionally clear views of the dispersal region and areas downstream. Under such ideal conditions, the satellite detected very slightly higher chlorophyll "streamers" immediately downstream of the discharge area. The size of the features, nutrient budget mass balance estimates, and images during other periods suggested that these small streamers result primarily from other forcing such as deeper localized mixing by wind. The slightly higher concentration in the streamers (~0.13–0.14 mg m^{-3}) relative to adjacent water was insignificant (an enhancement of 0.01–0.02 mg m^{-3}), but was detectable only because of the extreme sensitivity of the MODIS instruments on NASA research satellites. Traditional means such as ship surveys are unlikely to detect such small changes.

We concluded that we did not detect any apparent widespread chemical or biological effect (either positive or negative) in surface waters of the discharge area or downstream.

REPORT

Background

Detailed background information about the Piney Point phosphate water treatment and dispersal can be found at the Florida Department of Environmental Protection (FDEP) website at http://www.dep.state.fl.us/secretary/comm/2003/pp/background.htm. Here we briefly describe how the dispersal and monitoring plans were implemented.

In early 2001, the Mulberry Corporation abandoned its Piney Point phosphate fertilizer plant after claiming financial difficulty. This left 1.2 billion gallons of acidic wastewater unattended in open-air holding ponds, located along the southern margin of Florida's Tampa Bay estuary, threatening to spill into Tampa Bay as the ponds gained volume with seasonal Florida rains. For example, the spill of 50 million gallons of the acidic wastewater in December 1997 killed over 1 million fish and severely damaged local wetlands.

FDEP examined various possible approaches to eliminate the wastewater and impending danger to the fragile estuary. This included possible reuse in the reclaimed water system for irrigation in the region, discharging the wastewater (after treatment) into Tampa Bay through Bishop's Harbor, hauling the water to other holding ponds via truck or pipeline, or increasing storage capacity to help prevent spills. Continued heavy rains through early 2003, and detection of algal blooms in Bishop's Harbor forced FDEP to assess alternatives for disposal.

Among the options being considered was the option of treating the wastewater and disposing it in the ocean, i.e. in the Gulf of Mexico off the coast of Florida. Prior scientific studies of the circulation of waters on the West Florida Shelf (WFS) had revealed that nearshore waters off Tampa Bay did not move very rapidly (Yang and Weisberg, 1999). Further, the regular presence of the strong Loop Current farther offshore in the Gulf of Mexico, along the WFS edge, was a possible means to rapidly disperse the material. Offshore dispersal in waters of at least 200 m deep, within and along the eastern edge of the Loop Current, was considered appropriate.

In April 2003 the US Environmental Protection Agency (EPA) issued an emergency permit to FDEP to disperse over 500-million gallons of treated wastewater (to meet EPA standards) offshore in the Gulf of Mexico, provided that a monitoring protocol was implemented.

In the process of converging on options for the safe disposal, the State of Florida consulted with environmentalists, fishermen, resource managers, the general public as well as scientists of various backgrounds and disciplines. The proposed disposal caused concerns among the public about possible pollution, harmful algal blooms, water quality, and fishery impacts in the Gulf of Mexico, the Florida Keys, and adjacent areas. Various media reports provided extensive coverage of the series of events that led to the disposal process and about these concerns.

Several tools were examined to monitor the dispersal of the wastewater, including *in situ* water sampling with ships and on the barge, surface drifters for water movement tracking, numerical models for water movement prediction, and remote sensing using a variety of satellite-borne sensors. Aircraft surveys were considered, but the limited coverage, as compared with all possible water movement directions, restricted the use of such technologies.

The in situ surveys included water profiling at some pre-defined stations to study the hydrography, and water sample analyses (Charles Kovach, FDEP). The latter were to determine the bio-chemical and physical properties of the water, namely the nutrient content (NO_2, NO_3, Silica, NH_4, and PO_4; Dr. Kent Fanning, USF), algae (i.e., phytoplankton, via chlorophyll and phaeopigment; Dr. Gabe Vargo, USF) content, phytoplankton species composition (including the red-tide species, *Karenia brevis*, Dr. Brad Pederson, Mote Marine Lab), and colored dissolved organic matter (CDOM) abundance (via absorption coefficient). While some of the data are included here to help interpret the satellite imagery, our focus is on satellite data analysis.

Satellite remote sensing has been very useful in the past for the study of various large-scale oceanic features, and has proven to be an important tool to assess the potential impact of natural or human induced events. The satellite data were instrumental prior to the initiation of the dispersal to outline the area where the barge would operate to disperse the treated wastewater. In this Piney Point remote sensing monitoring project, we relied on satellite data analyses to provide real-time and accurate information on large-scale circulations and the position of the Loop Current, the strong oceanic current that would carry materials away from the dispersal region and therefore help minimize any possible coastal impact. In particular, we hoped to help answer the following questions with satellite remote sensing:

1) Where does the water discharged go?
2) Is the discharged water, or its impact on the environment detectable?
3) Was the coastal ocean around the Gulf of Mexico (i.e. Florida or elsewhere) affected?

Satellite Instruments, Color Interpretations, and Accuracy

Appendix A and B describe the methods used and the satellite data in detail. Briefly, the ocean color and temperature data are provided by various satellites on a daily basis under cloud-free conditions. These data are downlinked from the satellites, captured with ground antennae and processed by USF (http://imars.usf.edu). Occasionally, sea surface height (SSH) data from altimeters onboard satellites were used to help interpret the large-scale circulation features. These SSH data were provided by a group at University of Colorado (Dr. Bob Leben, http://www-ccar.colorado.edu/~realtime/).

The Dispersal Period: 20 July – 30 November 2003

The biological, chemical, and physical properties of the treated wastewater are summarized in Table 1. A total of 248 million gallons of this water was discharged into the Gulf of Mexico at the EPA-permitted locations through 35 barge trips (Table 2 and Figure 1).

Satellite Monitoring Results

This document focuses on satellite imagery (remote sensing), and describes only one part of the monitoring efforts being undertaken by several groups. Most elements in Table 1 cannot be directly monitored by satellites. The color data from satellites can only be used to estimate the content of phytoplankton, colored dissolved organic matter (CDOM), total suspended solids, and water clarity. The hypothesis underlying this study was that nutrients from the discharge (mainly N, P, Si) may have stimulated a phytoplankton bloom. Our task was to detect such a bloom, if any. Weekly and mid-term reports can be found at http://imars.usf.edu/Piney_Point/reports/, and daily satellite imagery can be found at http://imars.usf.edu/Piney_Point. Here we summarize our findings through the course of the monitoring project (20 July – 31 December 2003).

Other monitoring groups focused efforts on water sample analysis, and posted results independently (see Background).

Table 1. Biological, chemical, and physical parameters of the treated wastewater that is discharged into the Gulf of Mexico. Data source: Florida DEP.

Piney Point - Treated Water Summary							
Parameter	Units	02/28/03	03/06/03	03/13/03	03/21/03	Averages	Surface Water Standards
Acidity	mg/L	10	10.00	10.00	10.00	10.0	NS
Alkalinity -Total as CaCO3	mg/L	29.00	24.00	20.00	20.00	23.25	NS
Aluminum	mg/L	0.17	0.13	0.09	0.07	0.115	<1.5
Ammonia as N	mg/L					14.52	5.4***
Antimony	mg/L	0.08	0.002	0.002	0.002	0.022	<4,300
Arsenic	mg/L	0.0025	0.01	0.01	0.01	0.007	<50
Barium	mg/L	0.005	0.0050	0.0050	0.0050	0.005	NS
Beryllium	mg/L	0.0084	0.0050	0.0004	0.0005	0.004	<0.00013
BOD	mg/L	5.10	4.00	6.60	8.70	6.100	NS
Boron	mg/L	0.09	0.07	0.10	0.09	0.089	NS
Bromide	mg/L	0.25	0.25	0.25	0.25	0.250	NS
Cadmium	mg/L	0.02	0.000150	0.000150	0.00015	0.004	<0.0093
Calcium	mg/L	660.00	640.00	660.00	640.00	650.0	NS
Chemical Oxygen Demand	mg/L	43.00	41.00	87.00	39.00	52.5	NS
Chloride	mg/L	110.00	84.00	100.00	98.00	98.0	*
Chromium	mg/L	0.0025	0.0025	0.0025	0.0025	0.003	NS
Cobalt	mg/L	0.005	0.0050	0.0050	0.0050	0.005	NS
Color	pcu	10.00	10.00	2.50	5.00	6.875	NS
Conductivity	µs/cm	65000.00	5620.00	6670.00	6260.00	20,888	NS
Copper	mg/L	0.005	0.0050	0.0050	0.0050	0.005	<0.0037
Dissolved O2	mg/L	6.25	5.15	10.30	7.25	7.238	>5.0
Dissolved Orthophosphate As P	mg/L	0.05	0.05	0.05	0.18	0.083	NS
Fecal Coliform	/100mL	12.00	0.50	0.50	0.50	3.375	NS
Field pH	pH Units	7.16	7.01	6.78	6.66	6.903	*
Field Temp	Deg. C	21.40	24.20	23.00	25.20	23.45	NS
Field Turbidity	mg/L	5.47	3.74	1.83	1.60	3.16	<29
Fluoride	mg/L	1.20	<0.2	1.60	1.60	1.467	<1.5
Gross Alpha	pCi/L	24.0+/-6.4	<14.7+/-8.4	14.3+/-6.6	<13.7+/-8.8	13.1+/-5.4	<15
Gross Beta	pCi/L	156.0+/-8.4	139.0+/-13.6	139+/-8.2	142.0+/-12.4	144+/10.7	NS
Iron	mg/L	0.03	0.0250	0.0250	0.0250	0.025	<0.3
Lead	mg/L	0.0025	<0.005	0.0025	0.0025	0.003	<0.0085
Magnesium	mg/L	3.80	0.75	1.10	1.80	1.863	NS
Manganese	mg/L	0.00	0.002	0.002	0.002	0.002	<0.1
MBAS	mg/L	0.05	0.05	0.10	0.10	0.075	NS
Molybdenum	mg/L	0.03	0.0250	0.0250	0.0250	0.025	NS
Nickel	mg/L	0.03	0.03	0.03	0.03	0.029	<0.0083
Nitrogen, Total as N	mg/L					16.742	NS

NO2+NO3 as N	mg/L					0.806	*NS*
Oil/Grease	mg/L	2.05	19.00	19.00	4.30	4.3	*5.0*
Phenols	mg/L	0.05	0.005	0.005	0.005	0.016	*
Potassium	mg/L					133.81	*NS*
Radium 226	pCi/L	2.5+/-0.2	0.5+/-0.2	0.7+/-0.1	0.7+/-0.2	1.1+/-0.2	*<5*
Radium 228	pCi/L	<0.8+/-0.5	<1.0+/-0.6	<1.0+/-0.6	<1.0+/-0.8	0.5+/-0.3	*<5*
Selenium	mg/L	0.05	0.00	0.00	0.01	0.015	*<0.071*
Silica	mg/L	6.10	4.90	4.30	4.50	4.950	*NS*
Silver	mg/L	0.04	0.0035	0.0035	0.0035	0.011	*NS*
Sodium	mg/L					776	*NS*
Strontium	mg/L	1.70	1.50	1.70	1.70	1.650	*NS*
Sulfate	mg/L					3,495	*NS*
Sulfide	mg/L	0.5	0.50	0.50	0.50	0.500	*NS*
Sulfite	mg/L	5.00	0.32	0.36	0.52	1.550	*NS*
Thallium	mg/L	1	0.001	1	1	0.750	*<6.3*
Tin	mg/L	0.03	0.0250	0.0250	0.0250	0.025	*NS*
Titanium	mg/L	0.03	0.0250	0.0200	0.0250	0.024	*NS*
Total Chlorine	mg/L	0.05	0.050	0.050	0.050	0.050	*NS*
Total Dissolved Solids	mg/L					5,019	*NS*
Total Kjeldahl Nitrogen as N	mg/L					16.0	*NS*
Total Organic Carbon	mg/L	16.00	12.00	11.00	11.00	12.5	*NS*
Total Phosphorus as P	mg/L	0.55	0.32	0.23	0.26	0.340	*NS*
Total Suspended Solids	mg/L					6.990	*NS*
Uranium	pCi/L	5.7+/-1.3	2.0+/-1.0	3.3+/-1.2	1.0+/-0.7	3.0+/-1.1	*NS*
Vanadium	mg/L	0.005	0.0050	0.0050	0.0050	0.005	*NS*
Zinc	mg/L	0.08	0.04	0.08	0.08	0.065	*<0.086*

Notes: NS = No standard.
mg/L = Milligrams per liter.
pCi/L = Picocuries per liter.
µs/cm = Microhoms per centimeter.
*** the marine water quality standard for ammonia is based on several factors including pH, salinity and temperature.
The acute WQC of 5.4 mg/l is based on a salinity of 30 parts per thousand, a water temperature of 30 degrees Celsius, and a PH of 7.8, considered "worst case" conditions.
Absorption coefficient of colored dissolved organic matter (CDOM) at 400 nm (a proxy for dissolved matter, and can be estimated with satellite remote sensing) measured from the treated wastewater is 1.14 m^{-1} (data source: USF remote sensing), about twice lower than that found in the Mississippi water but fifty times higher than that from the clearest open ocean water.

Table 2. Statistics of the discharge operation of the treated water removal. Data source: FDEP.

		Discharge	Discharge	
Trip #		**Start Date/Time**	**Stop Date/Time**	**Gallons Discharged**
1	**Voyage #1**	07/20/03 - 15:25	07/21/03 - 17:00	5,396,311
	Coordinates	27*15.830N	27*24.018N	
		84*49.020W	84*51.037W	
2	**Voyage #2**	07/24/03 - 16:30	07/25/03 - 17:48	5,530,652
	Coordinates	27*18.731N	27*28.731N	
		84*49.302W	85*10.572W	
3	**Voyage #3**	07/28/03 - 19:15	07/29/03 - 24:00	5,466,914
	Coordinates	27*17.472 N	27*23.017N	
		84*51.418 W	85*00.814W	
4	**Voyage #4**	08/01/03 - 20:30	08/02/03 - 24:00	5,451,447
	Coordinates	27*17.480 N	27*23.014N	
		84*50.373 W	85*02.467W	
5	**Voyage #5**	08/05/03 - 15:00	08/06/03 - 18:00	5,353,070
	Coordinates	27*17.531 N	27*22.855N	
		84*50.721 W	84*51.802W	
6	**Voyage #6**	08/10/03-02:45	08/11/03-05:30	5,485,947
	Coordinates	27*17.72N	27*22.93N	
		84*52.72W	84*51.59W	
7	**Voyage #7**	08/13/03-19:45	08/15/03-05:30	6,867,999
	Coordinates	27*17.58N	27*25.75N	
		84*50.57W	84*49.69W	
8	**Voyage #8**	08/18/03-09:00	08/19/03-17:25	6,858,411
	Coordinates	27*17.42N	27*25.27	
		84*17.73W	85*12.10	
9	**Voyage #9**	08/22/03-16:00	08/24/03-00:30	6,917,177
	Coordinates	27*17.86N	27*23.72	
		84*49.54W	85*05.95	
10	**Voyage #10**	08/27/03-11:45	08/28/03-18:45	6,839,053
	Coordinates	27*27.89N	27*25.69	
		84*52.30W	84*51.76	
11	**Voyage #11**	08/31/03-20:30	09/2/03-06:30	6,911,853
	Coordinates	27*17.57N	27*26.18	
		84*50.00W	84*48.32	
12	**Voyage #12**	09/07/03-01:15	09/08/03-09:00	6,912,200
	Coordinates	27*18.21N	27*25.73	
		84*52.51W	85*54.06	
13	**Voyage #13**	09/11/03-11:30	09/12/03-20:00	6,954,098
	Coordinates	27*17.43N	27*25.97	
		84*50.66W	84*50.40	
14	**Voyage #14**	09/15/03-19:45	09/17/03-03:00	6,895,082

	Coordinates	27*17.48N	27*25.48	
		84*51.91W	84*56.34	
15	**Voyage #15**	09/20/03-07:45	09/21/03-13:42	6,942,704
	Coordinates	27*17.60N	27*25.52	
		84*49.15W	85*53.67	
16	**Voyage #16**	09/24/03-17:15	09/25/03-23:15	6,933,878
	Coordinates	27*17.48N	27*25.65N	
		84*49.96W	84*50.65W	
17	**Voyage #17**	10/01/03-20:45	10/03/03-'02:30	6,930,074
	Coordinates	27*17.50N	27*25.16N	
		84*50.00W	84*56.16W	
18	**Voyage #18**	10/06/03-09:15	10/07/03-15:42	6,894,653
	Coordinates	27*17.39N	27*25.86N	
		84*49.50W	84*54.09W	
19	**Voyage #19**	10/10/03-23:00	10/12/03-04:30	6,924,032
	Coordinates	27*17.24N	27*25.62N	
		84*49.50W	84*53.28W	
20	**Voyage #20**	10/16/03-21:00	10/18/03-02:15	6,919,015
	Coordinates	27*17.55N	27*25.40N	
		84*49.55W	84*54.69W	
21	**Voyage #21**	10/21/03-09:00	10/22/03-14:30	6,931,435
	Coordinates	27*17.92N	27*25.73N	
		84*50.60W	84*51.16W	
22	**Voyage #22**	10/25/03-22:30	10/27/03-04:00	6,947,606
	Coordinates	27*17.54N	27*25.64N	
		84*49.83W	84*49.21W	
23	**Voyage #1**	10/29/03-12:45	10/31/03-05:20	9,467,803
	Capt. HAD	27*15.2N	27*27.16N	
	Coordinates	84*44.6W	84*52.21W	
24	**Voyage #23**	10/31/03-20:00	11/2/03-02:00	6,963,303
	Coordinates	27*17.48N	27*25.56N	
		84*51.13W	84*49.50W	
25	**Voyage #2**	11/03/03-13:30	11/05/03-03:25	9,026,868
	Capt. HAD	27*16.46N	27*26.98N	
	Coordinates	84*44.83W	84*48.98W	
26	**Voyage #24**	11/05/03-20:30	11/07/03-02:15	6,968,198
	Coordinates	27*17.62N	27*23.00N	
		84*48.11W	85*38.71W	
27	**Voyage #3**	11/08/03-16:51	11/10/03-08:18	9,367,194
	Capt. HAD	27*14.24N	27*27.20N	
	Coordinates	84*44.09W	84*46.73W	
28	**Voyage #25**	11/11/03-08:00	11/12/03-13:25	6,959,670
	Coordinates	27*17.71N	27*25.59N	

		84*48.62W	84*52.72W	
29	**Voyage #4**	11/13/03-20:20	11/15/03-11:25	9,322,110
	Capt. HAD	27*13.50N	27*31.23N	
	Coordinates	84*45.24W	84*44.82W	
30	**Voyage #26**	11/16/03-03:15	11/17/03-08:45	6,960,508
	Coordinates	27*17.56N	27*20.27N	
		84*50.40W	85*08.11W	
31	**Voyage #5**	11/18/03-18:15	11/20/03-08:15	9,028,352
	Capt. HAD	27*13.57N	27*27.11N	
	Coordinates	84*43.68W	84*47.51W	
32	**Voyage #27**	11/21/03-08:00	11/22/03-13:30	6,977,897
	Coordinates	27*17.81N	27*23.20N	
		84*47.48W	85*25.20W	
33	**Voyage #6**	11/23/03-16:48	11/25/03-05:06	8,601,112
	Capt. HAD	27*13.35N	27*27.98N	
	Coordinates	84*44.29W	84*46.19W	
34	**Voyage #28**	11/26/03-08:00	11/27/03-13:45	6,965,087
	Coordinates	27*18.04N	27*15.73N	
		84*46.81W	84*50.18W	
35	**Voyage #7**	11/28/03-13:06	11/30-06:55	8,400,344
	Capt. HAD	27*13.24N	27*26.93N	
	Coordinates	84*44.50W	85*59.70W	
	Totals			**248,272,057**

Pre-dispersal Condition

Figure 1 shows the EPA designated dispersal location in the eastern Gulf of Mexico. The dispersal area, 120 miles offshore and > 200 m deep, is painted in light blue. The dispersal location, confined within this area, varied slightly due to ship operations and ocean conditions.

Figure 2 shows a MODIS (Esaias et al., 1998) satellite-derived "chlorophyll" composite image for 18-29 July 2003 (composite or average images are created over a few days to help minimize the effects of cloud cover). The image is overlaid with water depth (bathymetry) contours from 30 to 2000 m, the outline of the dispersal area (white box centered at about 27.2^{o}N 85.5^{o}W), a ship survey transect line, and locations of the fourteen ship survey stations where water samples from different depths were collected and analyzed during each of the eight survey trips between 9 July and 24 November 2003. Because the initial dispersal started on 20 July, pre-dispersal baseline information can be derived from this image and from the ship survey results.

In spite of the units provided on the color scale with Figure 2, the yellow-red colors along the coasts <u>do not</u> show high chlorophyll concentration. The values higher than 2-5 mg m^{-3} are mostly artifacts due to the presence of high colored dissolved matter concentrations derived from rivers and bays, suspended particles, and possibly some bottom light reflection effects. These factors led to false chlorophyll readings. Waters especially those along the coast can be relatively clear and still show these values in processed satellite images.

The southward flow of colored river water from the continental shelf of the northeastern Gulf of Mexico affected the waters near and on the West Florida Shelf in 2003 as it does every year. This plume contains water from the Mississippi River and other local rivers (Mobile, Apalachicola, etc.). In July 2003, these waters extended south in two plumes (indicated in Fig. 2 by arrows). One plume was parallel to West Florida Shelf (WFS), clearly crossing the western half of the dispersal area. The other extended southward over the middle of the shelf.

The pre-dispersal cruise survey to collect baseline water quality data in the Gulf prior to dispersion operations (transect line and station locations overlaid on Fig. 2) showed that salinity in the two river plumes was as low as 32 – 33 (grams per kg of seawater; Figure 3). Such low salinities offshore are evidence of river water. In contrast, Gulf waters typically have salinities higher than 35. Episodic rains cannot cause such a large and geographically focused salinity drop. The plume layer was about 10-20 m deep, as revealed by a depth-profiling instrument (conductivity-temperature-density or CTD). Water samples collected at several stations and different depths showed that waters with low surface salinities were accompanied by high content of colored dissolved organic matter (CDOM, with absorption coefficient as a proxy for concentration), but not always accompanied by high concentrations of chlorophyll. This is another evidence of river plume water.

The flow patterns of the river plume are typical of patterns seen during this season in at least the past five years as detected using satellite data from the SeaWiFS sensor launched in 1997. The southward flow from the northern coasts is driven by wind and surface heat flux (He and Weisberg, 2002), and by entrainment by major water circulation features (such as the Loop Current and its eddies).

MODIS Imagery Sequence and Large-Scale Features

Figures 4 to 24 show MODIS "chlorophyll" concentration and sea surface temperature (SST) images collected between mid-July and mid-October. On several images the surface tracks of

Argo floats (Jason Law and Robert Weisberg, USF) are overlaid. These floats move with currents. Current vectors from a numerical model (Naval Research Lab at Stennis, http://www7320.nrlssc.navy.mil/IASNFS_WWW/today/) are overlaid to show water movement patterns (Figs. 22 and 23). Frequently the dominant circulation patterns can also be inferred by changes in the color and/or SST of surface waters. Six areas of interest (for long-term studies of color changes) are outlined on Fig. 11. Explanation of relevant patterns and phenomena observed is included in the figure captions. Dominant circulation and/or suspicious features are marked on some of the figures.

Overall, the images captured daily and in near real-time (http://imars.usf.edu/Piney_Point) showed the dominant circulation patterns and the origins of some of the color features. For example the river plumes from the Mississippi and northern Gulf, and terrestrial runoff near Charlotte Harbor are clearly visible and trace the local and regional ocean water circulation.

The large-scale circulation features, the process of eddy shedding from the large Loop Current (see below), and the life of these eddies are consistent in ocean color and in the Sea Surface Height (SSH) data from satellite altimeters (data courtesy of Bob Leben of U. Colorado, http://www-ccar.colorado.edu/~realtime/), as shown in Figures 25-33. They are also consistent with those from numerical modeling, as shown in Figures 22 and 23. The combination of satellite imagery (ocean color, SST, and SSH) and numerical models shows unambiguously the large-scale features such as the Loop Current, large-scale eddies (see below), and river plumes.

Three dominant large-scale circulation features were observed from satellites. First is the Loop Current, which plays a major role in the circulation of the Gulf. The location, spatial extent, and temporal variations of this current are very dynamic and still a subject of research. Near the beginning of the dispersal, the northeastern edge of the Loop Current coincides with the dispersal area (Fig. 4). This ensures rapid dilution of the discharged water along the Loop Current towards the south.

The enhanced color to the south of the southeastern corner of the dispersal area is natural, and due to enhanced biological activities along the edge of the Loop Current (the Loop Current edge is outlined in the image). This is the result of nutrients provided by upwelling of deep water along the Loop Current edge and also by colored water from the Mississippi River plume. Enhanced colors around cloud edges are algorithm artifacts. Overlaid on the image are the locations of two Argo floats (red crosses. Argo data courtesy Jason Law and Robert Weisberg, USF) that flow with the currents. Also overlaid on the image are bathymetry (water depth) contour lines. The difference between the float position and the color patch position around 24^{o}N 84.5^{o}W is due to the southward movement of the water mass from 1 August (image date) and 4 August (float date). This effect is more apparent in Figure 5 where the image was captured ten days later, on 10-11 August. The Loop Current has persisted through the whole monitoring project, yet its north most position retreated southward to about 24.7^{o} in early October (Figs. 9 and 10), and then moved to north in late December (Fig. 33).

Second, a large (>200 miles in diameter) anti-cyclonic (clockwise) eddy was shed from the Loop Current in mid-September to early October (Figs. 8-10), and persisted in the region until late December (Fig. 33). The eddy remained stable but the northern edge of the Loop Current retreated to a southern position at about 24.7^{o}N. This is a natural phenomenon that has been observed repeatedly since satellites have observed the ocean. One of the floats was caught in this large eddy (Fig. 10).

Finally, the Mississippi River plume persisted in the northeastern Gulf throughout the monitoring project, especially between late May and late October. Near the dispersal area, the river water from the northeastern Gulf of Mexico (particularly the Mississippi delta and Mobile Bay) was apparent.

The presence of this river water is not directly related to Mississippi river discharge volume (which showed no significant increase at this time compared with previous years as monitored by USGS river gauges). We speculate that wind played a role in detaching the river water from the northern coasts and forcing it offshore, where the Loop Current and its large eddies may have "dragged" the plume towards the south.

Figures 34-36 show the mean weekly wind between 14 May and 10 June, between 6 August and 16 September, and between 15 October and 11 November, respectively. In response to the Coriolis effect (an artificial force defined to describe the effect of the Earth's rotation on moving objects as viewed by an observer on Earth) the surface current in the northern hemisphere moves up to 45 degrees to the right of the wind direction. During the period covered here, winds in and near the Piney Point dispersal area were relatively weak (order of 10 m/s or 19.4 knots or less). Wind at any moment during the average period may have been stronger and of varying direction.

The dominant north to northeastward wind between late May and early August may have caused the Mississippi River to flow east and southeastward.

The strong northward and northwestward wind in late August, and subsequent wind in early September (Fig. 35) around the dispersal area may have contributed to the dissipation of the river plumes as observed in the satellite images, since these plumes are shallow and contain less dense water masses relative to the oceanic water in the Gulf. This dissipation was also accelerated by the shedding of a Loop Current eddy, which led to the contraction of the Loop Current to the south, the westward shift of the eddy, and therefore removing the mechanism to advect water from northern shelf area.

The large-scale features documented here represent major dominant biogeochemical and physical conditions over our study area.

Small-scale Features

Following the Loop Current pathway and in the Florida Straits, there were some small-scale water color patches that merit interest. These are not associated with the Piney Point discharge. Because of the difficulty in understanding the large spatial scales of phenomena in the Gulf of Mexico, some members of the public called attention through various media reports to anomalous color of water near the Florida Keys, and posed the question as to whether there was a connection to Piney Point. Many of the anomalies near the Florida Keys occurred in late August, as shown in Figure 37. These patches resulted from one or more of the following mechanisms: river plume water moving along the edge of the Loop Current, local upwelling from small eddies, or water intrusion from Florida Bay (see the 09/02/03 image in Fig. 17). Chlorophyll concentrations in these color patches ranged from 0.15 to 0.5 mg m^{-3}, compared with <0.1 mg m^{-3} in the nearby Gulf Stream waters.

Algal blooms near the Florida Keys National Marine Sanctuary (FKNMS) are known to stress local ecosystems (Hu et al., 2003a). However, the elevated chlorophyll near the Keys at the time of this study was not analogous to the 2002 "black water" event in terms of size or intensity. The "black water" was thought to be caused by both earlier red tide and local river runoff (SWFDOG, 2002); it lasted for about four months and contained high levels of chlorophyll (5-10 mg m^{-3}) and CDOM (~0.3 m^{-1} at 400 nm) and also red tide species of up to 10,000 cells/L. In contrast, the colored patches near the Keys (ocean side) during this study contained chlorophyll and CDOM of about 0.15-0.5 mg m^{-3} and 0.02-0.05 m^{-1}, respectively. Nearby clear Gulf Stream waters contained about 0.08 mg m^{-3} and 0.015 m^{-1} CDOM. This is an order of magnitude smaller.

Starting in early October, we observed a "flushing" phenomenon that led to coastal waters from near Charlotte Harbor to disperse toward the Dry Tortugas, and around the Florida Keys. Figure 38 shows a series of MODIS images to describe the event. Clearly, the "black water" patches described by local fishermen south and southwest of Key West (annotated in the last panel of Fig. 38), were due to runoff near Charlotte Harbor and near the Ten-thousand Islands. Florida Bay might have also contributed colored water to this event. In terms of chlorophyll concentration, however, the intensity is 3-5 times less than that found in the early 2002 "black water" patches. This flushing event was apparently wind-driven, as the dominant wind in the region from early October to late November was southwestward (Fig. 36). Earlier images showed that there were dark water patches in the coastal areas near Charlotte Harbor in September 2003, possibly from higher than normal rainfall-induced river runoff during late summer. These dark waters were driven by the October wind to flow southwestward. The dark water patches found near the Keys and Dry Tortugas are therefore related to this type of local runoff, not to the Piney Point discharge.

Piney Point Water Detected?

We posed the following question: Is it possible that the discharged Piney Point water contributed to a color change in and around the dispersal area?

A nutrient mass-balance estimate suggests that any change in phytoplankton concentration as a result of the discharge is likely to be very small to negligible, given sufficient dilution. From sample analysis of the barge water and nutrient budget estimates (Table 1), if the discharged water was diluted rapidly then the biological and color effects should be small. Samples taken from the Piney Point treated water on the barge show that absorption coefficient of colored dissolved organic matter (CDOM or a mixture of naturally-occurring tannic and fulvic acids) at 400 nm (ag400, a proxy for CDOM concentration in the sample) was about 1.14 m^{-1}. For reference, Mississippi water at the mouth of the river delta at this time of the year is about 1.9 m^{-1}; the open Gulf clear water is about 0.03 - 0.04 m^{-1}. Phosphorus concentration was about 340 mg m^{-3} in the treated wastewater (Table 1). A simple dilution of 1:2000 within a few hours (according to EPA's plume model) would result in an addition of 0.00057 m^{-1} for CDOM and 0.17 mg m^{-3} for phosphorus, respectively. This level of CDOM cannot be detected with either satellites or sensitive ground-based equipment. Based on the measured phosphorus:chlorophyll ratio (1.7 weight:weight; Vargo et al., in review), the discharged phosphorus could support chlorophyll growth of up to 0.1 mg m^{-3} after dilution, which is comparable to the background level of the open Gulf. Further dilution, such as that which may be effected by mixing and dispersal along the strong Loop Current, would render any accumulation of algae biomass due to growth by nutrient addition undetectable.

The dilution rate estimated by EPA's plume model, 1:2000 within a few hours, was not experimentally confirmed. However, data from other sources indicate that it may be a conservative estimate. Dilution rate of commercial cruise lines is typically in the range of 1:50000 within minutes (Oceans2003 conference, 22-26 September 2003, San Diego, CA). The presence of the Loop Current, local circulations of eddy, and river plumes, may result in a significantly higher dilution rate.

The question is what roles satellites may play in monitoring. If the water had been stagnant and nutrients were to be added continuously to the same location, or the location of dispersal had been free of river plume and waters were very clear, then the chances for detection would be very high if a bloom were to develop. During the whole dispersal course there were only a few days when perfect weather and viewing conditions were met, and when river plumes were absent from the area. The satellite data was also, as mentioned above, instrumental in defining the dispersal area that would lead to rapid and continuous advection and dilution of wastewater far away from the coast and shelf environments.

The whole dispersal area and its immediate downstream area (south of the dispersal area) remained under consistent influence of river plume water and/or productive water carried along the Loop Current until early October. During the period of river influence, it was not possible to detect any enhanced color in the area due to the treated wastewater. Starting in early October, although the discharge area was free of river water (or Loop Current edge blooms), scattered clouds within the dispersal area and cloud-adjacency effects in the algorithms made it difficult to obtain the perfectly clear image that may have been ideal to detect the small discharge stream. On 15 October 2003, a cloud-free image was obtained due to passage of a cold front which was also free of river interference (Figures 12-15). This was an opportunity for close examination of the possible larger-scale effects of the discharge.

The barge discharge before the clear image occurred on 10 and 11 October. The expected effects from the discharge would be downstream (south of the dispersal area) and within the large anti-cyclonic eddy present in the area as identified in Fig. 12 (area of very low chlorophyll concentrations to the south and southwest of the discharge region).

The 15 October 2003 chlorophyll image (Fig. 12) was artificially enhanced by stretching the contrast and re-coloring. This helps examine spatial patterns in the color of the water in the area of low chlorophyll concentrations immediately south of the dispersal zone (see Fig. 13). The color-enhanced and stretched image shows some streamers of colored water within the northeastern portion of the eddy. These were identified and annotated on Fig. 13 (same image as Fig. 12 but with contrast stretched).

The color streamers (light blue-green color) correspond to chlorophyll concentrations of approximately 0.12-0.14 mg m^{-3}, or only slightly higher than concentrations in the surrounding clear water of the eddy in the Gulf of Mexico (of 0.1- 0.11 mg m^{-3} or dark blue and purple color on Fig. 13).

The question that arises is what is the cause of the slightly elevated (20%) phytoplankton biomass concentrations. Are they associated with the treated wastewater discharged five days earlier, or are they related to other processes such as vertical mixing of surface waters in the region? Such mixing may be due to sustained winds and may result in waters from below the surface to be mixed upwards; such waters would typically have slightly higher nitrate and other nutrient concentrations and would stimulate plant growth when exposed to light. This is a normal and common process in the Gulf. We explore these two scenarios below.

As discussed in previous reports, at a dilution rate of 1:2000, the additional CDOM absorption is negligible. It cannot be detected by either satellites or sophisticated lab instruments. The maximum phytoplankton growth after 1:2000 dilution that would be supported by the nutrients in the discharged water is estimated to be about 0.1 mg m^{-3}. Five times more dilution would reduce this to 0.02 mg m^{-3}. This is consistent with the color streamers that are observed in Fig. 13. The total volume discharged from the 10-11 October dispersal effort was about seven million gallons, or 26,498 m^3. After 2000×5 dilutions, the total volume is about 2.65×10^8 m^3.

For a water layer of about 5 m thick, this would cover about 53 km^2, i.e., about 53 satellite pixels in Fig. 13. The area outlined with a white ellipsoid trace in Fig. 13, just south of the dispersal area, encompasses 9,544 pixels. There are 3422 pixels with chlorophyll concentration > 0.12 mg m^{-3} and 191 pixels with > 0.13 mg m^{-3}.

If 0.13 is used as a threshold for apparent "new" phytoplankton growth, then about 28% (53 / 191) of the growth might be due to the 10-11 October discharge. This is a very rough estimate based on the assumptions of 1:10000 dilution, 5 m water layer, and complete nutrient consumption. If the water discharged prior to 10 October was also entrained in this eddy, the contribution to the phytoplankton growth could be larger. However, it is important to realize that concentrations of 0.13 or 0.15 mg m^{-3} are typical in open waters of the Gulf of Mexico, as seen throughout the image, and should be considered normal.

The chlorophyll concentrations discussed above are not from field measurements, but from MODIS estimates (Aqua satellite, SeaWiFS-analog algorithm). MODIS real-time data are only "provisional" and may be slightly off in accuracy (not precision), because of the time lag for calibration and algorithm updates. However, it is the relative contrast we are focusing on, therefore the provisional quality doesn't affect our findings.

The eddy recirculation patterns seen in the MODIS ocean color images can be identified also in Sea Surface Temperature (SST) infrared satellite imagery from both the AVHRR and MODIS sensors. Figure 14 show the SST image obtained from MODIS on 15 October 2003 (same satellite overpass as in Figs. 12 and 13). The large anti-cyclonic eddy in the central Gulf of Mexico can be clearly seen. After color contrast stretching, SST details downstream of the dispersal area are revealed (Figure 15 in the outlined area). There is a slight (0.1–0.2^{o}C) SST drop in the area where chlorophyll "streamers" are found. Deeper mixing with the bottom cold water might have occurred, which brought the bottom nutrient to the surface to stimulate phytoplankton growth. Yet it is difficult to confirm or discount such hypothesis due to lack of information in the hydrography of the eddy (mixed layer depth, depth profile of nitrate, etc.). Historical data (Biggs, 1992) show that within a large anti-cyclonic eddy in the Gulf, mixed layer depth is typically 50-100 m, and the nutri-cline depth is slightly larger. Wind prior to and near 15 October 15 was around 10 m/s or higher (Fig. 36). Persistent strong wind may have brought some nutrients to the surface if the nutri-cline was shallower than shown in Biggs (1992).

Satellite SST reflects only a "skin" (sub-millimeter) surface temperature, while chlorophyll is a parameter of the surface layer of tens of meters in clear ocean water, as in this case where the streamers occurred. For the phenomena observed above, we expect that if there was any field survey including only a few sampling stations, the pattern of the streamers would be difficult to detect. This slight difference (0.01-0.02 mg m^{-3} chlorophyll and 0.1–0.2 ^{o}C SST) is easily interpreted as instrument noise. The patterns observed from the MODIS instrument are, however, real. The cause is unclear without more detailed concurrent 3-dimensional surveys.

Similar color "streamers" were also found in subsequent MODIS images (Figs. 16-20). Although there is no direct evidence linking them to deep mixing, the size of these streamers and patches suggest they could not have resulted from the discharge alone due to the limited nutrient supply from the discharge. We suspect that they may be partially related to the discharge. In any event, the contrast between chlorophyll levels in the streamers and in the surrounding waters is extremely low (0.01–0.02 mg m^{-3}), and detectable only because of the extraordinary sensitivity of the ocean color observation channels in NASA's MODIS satellite sensors and the fact that the satellite also measures an extensive area as a "snapshot." It would be difficult if not impossible to detect these, and reconstruct their spatial extent, from ship-based observations.

Minimal Algal Concentration Increases

Because the primary purpose of the monitoring was to document whether there was any impact of the discharge on near-shore environments, a long-term change detection study was designed and implemented for several shelf and coastal waters as part of this effort.

We chose six areas (see Figure 11: Areas #1 to #6) to characterize biological activity during pre-dispersal conditions. Areas 1 to 3 are on the West Florida Shelf (WFS), one in water depth <30 m (waters with extreme turbidity/bottom interference were excluded to improve quality control), one in 30-50m, and one in 50-100m off central western Florida. Area 4 is in the Florida Strait in water depth 200-500m. Area 5 is closer to the coast and covers only the near shore waters of the lower Keys. Area 6 is to the southeast of the dispersal area in deep waters and also overlapping the deep shelf. The surface area for each area of interest sampled is about 6450, 7213, 12708, 4892, 3097, and 37660 km^2, respectively.

Monthly mean satellite ocean color data spanning the period September 1997 - December 2003 were derived from SeaWiFS (McClain et al., 1998) with a semi-analytical algorithm (Carder et al., 1999; Hu et al., 2003b). The following products are shown in Figures 39 - 41:

- surface chlorophyll concentration in mg m^{-3} and
- CDOM absorption coefficient at 443 nm in m^{-1}.

These data have been validated by extensive cruise surveys. The uncertainties of the values measured are generally within ±35% (note that this is a root-mean-square uncertainty, not a bias) for the deep water (> 30 m) where there is no significant riverine impact (see Appendix B and Hu et al., 2003b). The near shore values, particularly close to the coast (waters shallower than 30 m) are likely less accurate.

Our results show that none of the six areas showed significant increase in chlorophyll concentration since the dispersal was initiated on 20 July 2003. This shows that shelf and coastal waters had similar phytoplankton concentrations in 2003 compared to other years even during the period of the discharge (July – November 2003). In December 2003, Areas 2, 4, and 5 showed slightly higher than normal chlorophyll concentration due to upwelling or coastal runoff (see anomaly images below). The waters immediately downstream of the dispersal area, Area 6, showed no enhanced chlorophyll throughout the monitoring period (July – December 2003).

There were several cases when elevated colored dissolved organic matter (CDOM) was seen in areas removed and disconnected from the dispersal area:

1) Area 1 in September 2003 - this may be an indication of terrestrial runoff that carried excessive amount of CDOM; Summer 2003 received significantly higher than normal rainfall over central Florida than previous year.
2) Area 3 and Area 4 in August 2003 – this indicated significant influence of the Mississippi plume or other northern rivers;
3) Area 6 in July and August 2003, which was also due to river plume.
4) Areas 1-5 in December 2003, due to coastal runoff and deeper winter mixing.

The abnormal behavior of 1998 in terms of higher concentrations of CDOM and higher riverine influence was possibly related to El-Nino, which was associated with unusually high rainfall in the drainage basins for these rivers.

The areas in this study were carefully chosen to represent all potential affected areas. They were chosen to optimize spatial coverage and minimize the number of graphs required to present time series for the region. It would be impossible to present similar graphs for every pixel in the study area. However, such analyses can be performed for any particular location. For example, we received a report of possible water quality degradation to the northeast of the Dry Tortugas from a fishing boat captain, which prompted us to focus a time series analysis (1997 – 2003, see Report #3) of the water clarity at the reported location. The satellite images showed that the decrease in water clarity at the location was clearly and unambiguously connected to the river plume advected from the coast of the northern Gulf of Mexico to the Florida Keys.

Although it is impossible to present a similar graph for each location (pixel) on the image, an image "differencing" exercise may reveal changes in phytoplankton biomass at each pixel. Figures 42-47 show SeaWiFS-derived chlorophyll difference (NASA standard band-ratio algorithm) between 2003 and 2002 for the month of July to December, respectively. Clearly, for July and August, the positive values (green color means higher chlorophyll concentration in 2003 than in 2002) are due to either Mississippi River plume and/or enhanced productivity along the Loop Current edge. For the rest of the months, the dispersal area and its surrounding and downstream areas show near-zero or negative values, indicating no enhanced biological activity compared with 2002. No positive value (green color) between September and December (Figs. 44-47) is likely related to the discharge, as evidenced by the context and location of these green-colored areas.

From the above analysis, we concluded that there was no evidence of significant increase in phytoplankton growth or concentration between August and December 2003 in areas downstream of the wastewater dispersal zone. The increase in CDOM in some remote areas disconnected from the discharge area was due to the influx of river-derived waters originating in the northern Gulf of Mexico, and/or deeper winter mixing due to strong wind.

In all areas examined, the chlorophyll and CDOM levels are similar to those seen in other years and should be considered normal.

Where Does The Water Go?

The MODIS ocean color imagery clearly showed that the discharge area was within the influence of the Loop Current, i.e. either near the Loop Current edge or within the Loop Current itself or within a large anti-cyclonic eddy (as the one shed in early October 2003). We therefore inferred that before early October the discharged water moved to the south/southeast, carried by the Loop Current, and that it moved to the Florida Straits and then into the Atlantic Ocean by the Gulf Stream along Florida's east coast. After early October, the discharged water may have moved to the south/southwest, entrained by the large anti-cyclonic eddy. Such motions are mimicked by numerical computer models (Figs. 22 and 23 for example) and confirmed by direct observations from surface drifters and satellite altimeter data, as shown in Figs. 4-10. Only one of the eighteen surface Argo drifters, released in the dispersal area from five ship surveys (Jason Law and Robert Weisberg, USF), moved to the north (float #20087, see Report #10). This drifting float did not reach the coast before battery ran out. One drifter was caught in the anti-cyclonic eddy (Fig. 10). Most of the drifters moved to the south and ended up in the Atlantic or in the central Gulf during the 3-month battery life. None of the drifters ended up in coastal regions.

The southeastward transport of river discharge water in the Gulf of Mexico has been observed repeatedly every year since 1998, when SeaWiFS data became available after the launch of this satellite in late 1997. The timing and strength varied from year to year. Figure 48 shows a SeaWiFS composite chlorophyll image from July 24th to July 29th 1999. The water trajectory outlined by the yellow and green colors offshore and along the WFS shelf break is remarkably similar to what was observed in early August 2003. Such a flow pattern in the northern Gulf is driven mainly by entrainment of shelf water in the northern Gulf of Mexico into the Loop Current, and also by wind and surface heat flux. During the spring, offshore transport of shelf water in the northeastern Gulf takes place immediately south of Cape San Blas, and in this case the driving mechanism is the density difference between the cold shelf waters and the warm offshore waters (Yang and Weisberg, 1999; He and Weisberg, 2002).

Temperature Imagery

Daily images of sea surface temperature (SST) from AVHRR and MODIS have been generated and placed online for public use. The images collected during summer 2003 did not reveal much as SST is typically homogeneous in the Gulf at this time of the year. Only until late September and early October did the images start to show large-scale features such as the large eddy and the Loop Current (e.g., Figs 14, 15, 17, 21). These images complemented the ocean color imagery for large-scale feature identification, as the four AVHRR sensors and two MODIS sensors increase the spatial coverage and minimize the impact of cloud cover. The use of SST data helps identify possible upwelling or deep mixing events, as shown in Fig. 15.

Field Samples

Sample analysis was necessary to provide direct evidence of the biological and chemical content of the water. Most of the samples collected for the Piney Point offshore discharge program have been analyzed by other groups at USF and Mote Marine Lab, and results will be posted separately. Our water sampling effort focused on the water CDOM content, mainly to help interpret the satellite signal, because the color of the river plume water is due in a large part to CDOM. CDOM is also used to trace fresh water, as elevated CDOM often indicates presence of river plumes.

The samples were taken mainly from some of the fourteen pre-determined stations, as shown in Figs 2 and 49. Figure 49 shows a MODIS chlorophyll image for 26 August 2003 with station locations overlaid. The image shows that similar to the pre-dispersal image (Fig. 2), there were two river plumes: one crossing the western part of the dispersal area and one to the east of the box. This has been confirmed with nearly concurrent field data. Figure 50 shows CDOM absorption, salinity, and chlorophyll concentrations in surface waters from the 27-28 August survey. Similar data from the 3-4 September survey are shown in Figure 51 (chlorophyll and salinity data courtesy of Danylle Spence-Ault and Gabe Vargo, USF).

Because the satellite data and field surveys are not strictly concurrent, and because of the eastward movement of the Loop Current edge, although in Fig. 50 it would appear that ST 7 and ST 8 are located in high-chlorophyll water, field data show low chlorophyll, low CDOM, and high salinity for these two stations. The river plume on the eastern side of the dispersal area was confirmed by the low salinity, high CDOM, and high chlorophyll data from the cruise survey.

The increase of chlorophyll from high-salinity Gulf waters to low-salinity plume waters is proportional to that of CDOM, both by a factor of 2-3 (Figs 50 and 51). This implies that there was no significant "new" chlorophyll growth, but rather shows a mixing process associated with the river plume. Typically, waters with "new" chlorophyll tend to have elevated chlorophyll but rather stable CDOM. The rest of the data showed similar trends. As a summary, Figure 52 shows the comparison between surface CDOM and chlorophyll obtained from some of the 14 stations during the 8 ship surveys between early July and late November. Under most circumstances, CDOM increases with chlorophyll, while in cases of river influence increases in CDOM dominated those in chlorophyll.

Conclusions

For the period of 20 July to 30 November 2003, a barge conducted thirty-five trips to discharge approximately 248 million gallons of treated Piney Point wastewater in the Gulf of Mexico. Through analysis of satellite imagery (ocean color, altimetry, and temperature), field samples, and ancillary data such as wind and river discharge, we did not observe any impact of the Piney Point discharge on either surface chlorophyll concentration or CDOM content on the West Florida Shelf or areas near the Florida Keys. Surface concentrations of both phytoplankton and CDOM are comparable to those observed in five previous seasons (1998-2002). The chlorophyll and CDOM levels in the areas examined in 2003 should be considered normal. We attributed this to relatively low total nutrient and water volume released from each discharge, particularly when compared with the amount of water reaching the same area from the Mississippi River and adjacent rivers, and rapid dilution by ocean currents such as the Loop Current.

A long-term analysis was performed to assess change over large areas (> 3000 km^2). The chlorophyll difference images, derived from the well-calibrated SeaWiFS sensor for the months of July to December between 2003 and 2002, showed no evidence of enhanced biological activity near or downstream of the discharge area. All enhanced biological activity in 2003, as compared with the same month of 2002, occurred in coastal regions completely disconnected from the Piney Point discharge as revealed in part by the geographic context of these features in the images, by numerical models, and by surface drifter data.

Only in a few cases and starting 15 October 2003 did we detect some suspicious features in the form of elevated chlorophyll "streamers" immediately downstream of the discharge area. These features may have partially resulted from the discharged water, which is nutrient rich. But the size of the features and simple nutrient budget estimates suggest that most of them were the result of natural processes, such as deeper mixing under strong wind. In any event, the slightly elevated concentration (~0.13–0.14 mg m^{-3}) should be regarded as normal for open Gulf waters. The enhancement (0.01–0.02 mg m^{-3}), as compared with surrounding waters, was detectable only because of the extreme sensitivity of MODIS instruments. Traditional means such as ship surveys will likely interpret any signal of this small magnitude order as instrument noise.

The small dark-water patches reported by local fishermen and seen in the satellite data near the Florida Keys in late August and early September were due to river influence rather than from the discharge. This is more apparent in late October and November, when similar dark water patches were found unambiguously result from coastal areas near Charlotte Harbor and therefore had nothing to do with the Piney Point discharge.

Satellite data analyses provided real-time and accurate information on the position of the major currents that would carry materials away from the dispersal region and minimize any possible coastal impact. The satellite data were instrumental prior to the initiation of the dispersal to outline the area where the barge would operate to disperse the treated wastewater. Without the weekly satellite data analysis, it would have been impossible to tell which way dispersed waters were likely to move. Historical satellite data provided the unique baseline information that was critical to evaluate oceanographic conditions considered as "normal." The satellite ocean color data played a critical role in the effective monitoring of the ocean's biological state. Summertime SST data revealed fewer features than ocean color data. Similarly, SSH or numerical model data provided little information over shallow coastal waters.

Acknowledgements

This work was supported by the FDEP. We thank NASA Headquarters (Dr. James Dodge) and SeaSpace Corp. for their support and assistance to establish and maintain the MODIS data receiving station. We thank Drs. Robert Weisberg and Ruoying He (USF) and Drs. Dong Shan Ko and Ruth Preller (Naval Research Lab at Stennis) for discussions on ocean circulation. We thank Dr. Bob Leben (University of Colorado) for providing the satellite altimeter data. We also thank Doug Myhre, Judd Taylor, Brock Murch, Zhiqiang Chen, Danylle Spence-Ault, and Bisman Nababan (USF) for their assistance in collecting and preparing the satellite and field data. SeaWiFS data are property of Orbimage Corp., and are used here in a research mode and therefore in accordance with the SeaWiFS Research Data Use Terms and Conditions Agreement of the NASA SeaWiFS project.

Figures

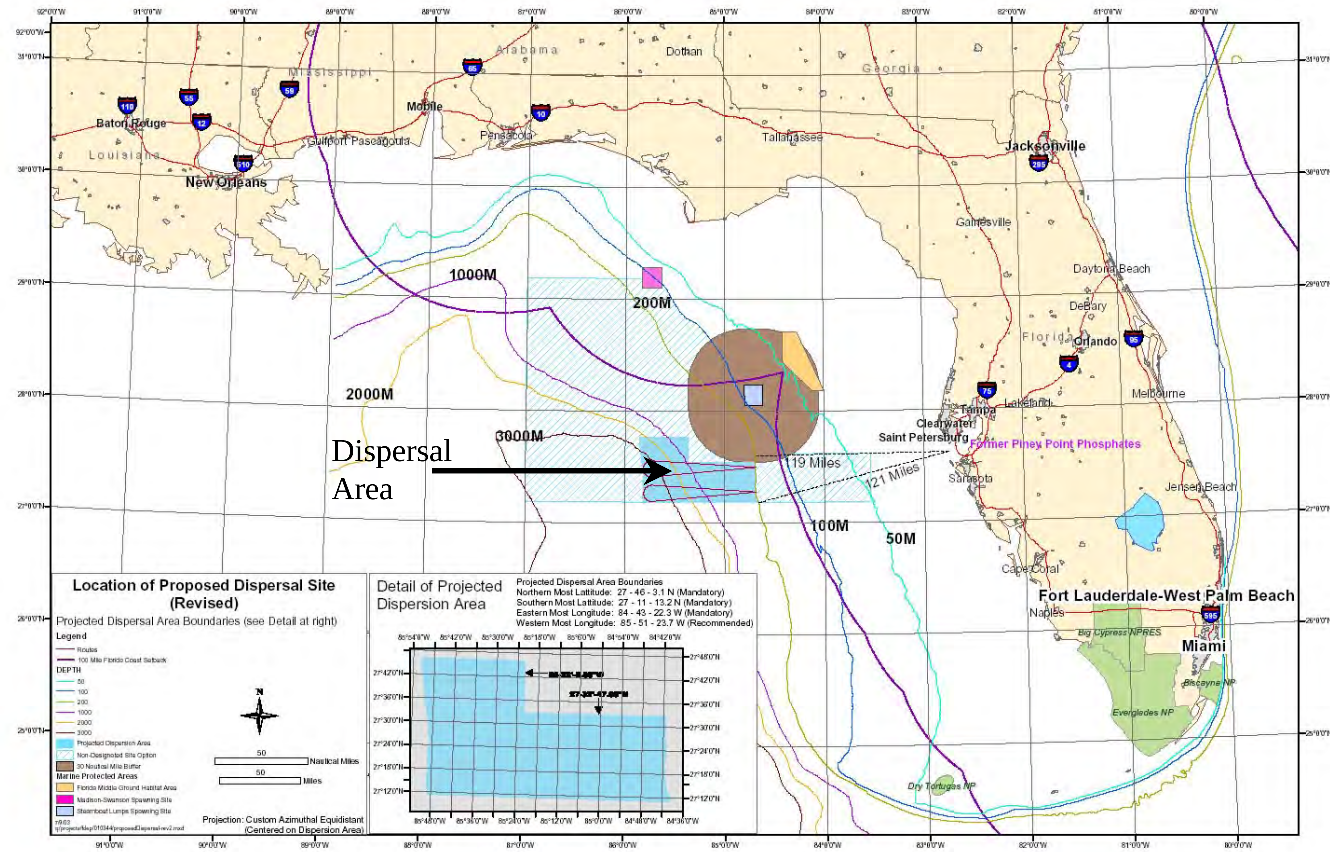


Figure 1. Dispersal area, shaded with blue color. The area is 120 miles offshore at water depths > 200 meters.

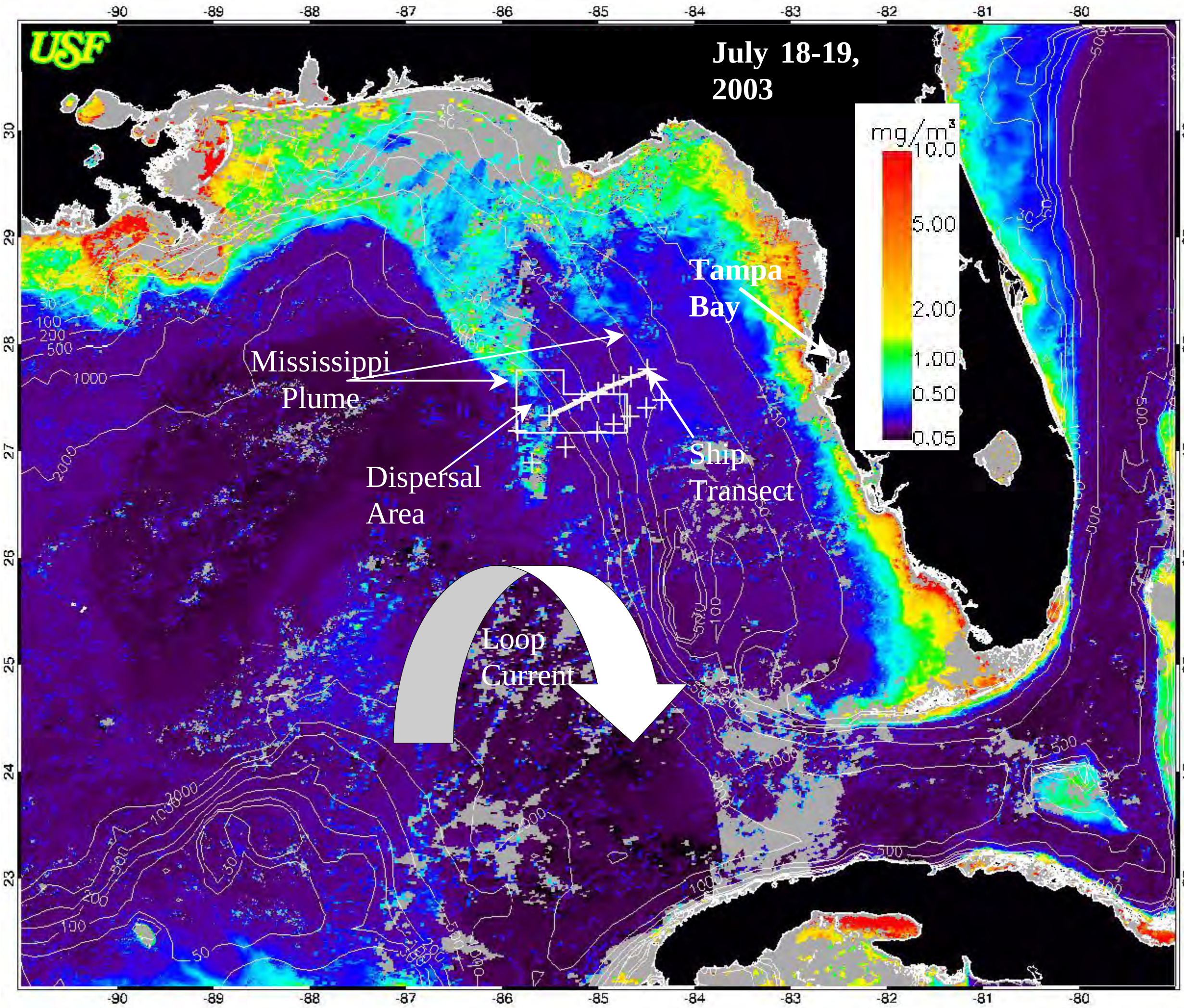


Figure 2. MODIS chlorophyll image for 18-19 July 2003, before initial dispersal on 20 July. The dispersal area is outlined as a white box. Also overlaid are the bathymetry contours, from 30 to 2000 m. One major current, the Loop Current, is outlined on the image. A ship transect during 9-10 July 2003, which detected low salinity (32-33, Figure 3) waters, is overlaid on the image. The fourteen stations where water samples were collected and analyzed during each of the eight ship surveys between 9 July and 24 November 2003 are marked as "+" on the image, in the order of starting from top right, running towards west and then south, and then running towards east.

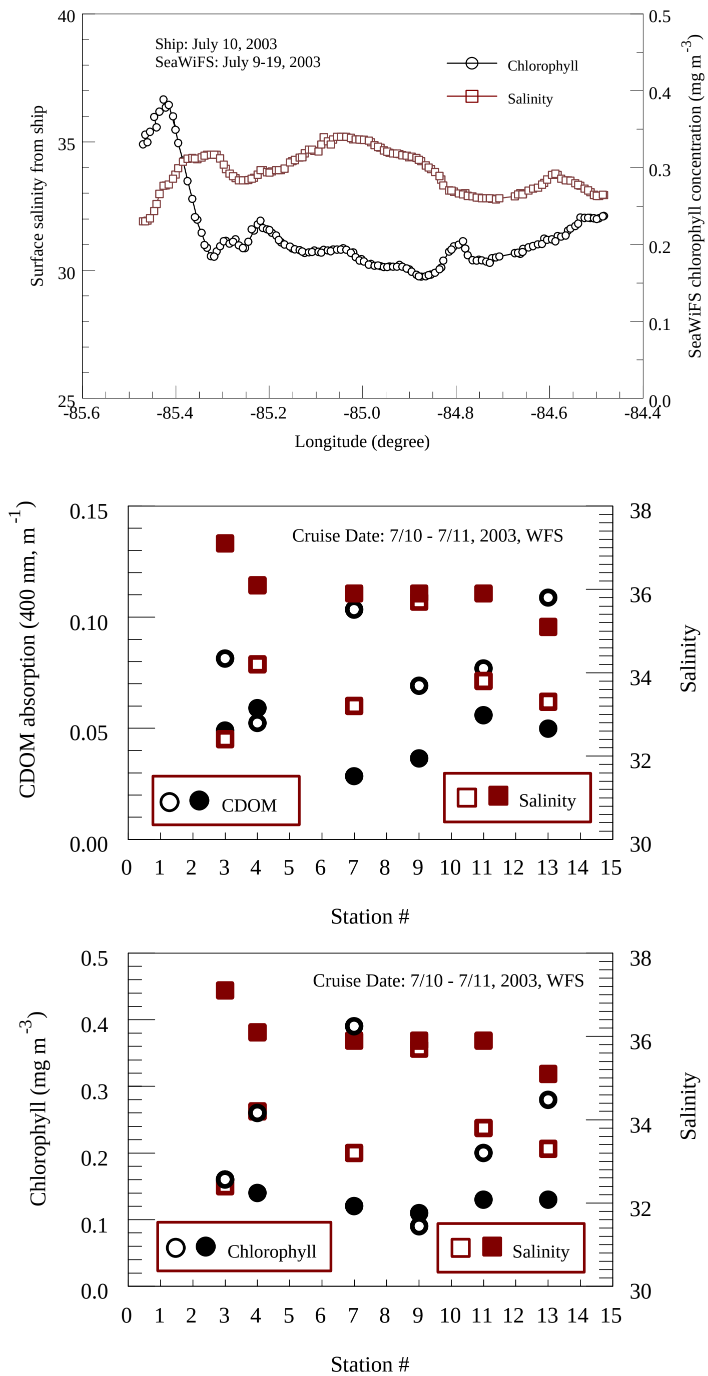


Figure 3. Biophysical and chemical data collected during the 9-10 July 2003 ship survey (see Fig. 2 for locations). Top: Surface salinity from ship survey and surface chlorophyll concentration from SeaWiFS along ship transect. Low salinity values indicates river plume. Middle and bottom: surface and subsurface (at 20-35 m water samples were collected from CTD bottles) properties at several sampling stations (surface: empty symbols; subsurface: solid symbols). Waters with low surface salinity values are accompanied with high CDOM values, but not always with high chlorophyll values. The low salinity (river plume) layer is around 15-20 m deep.

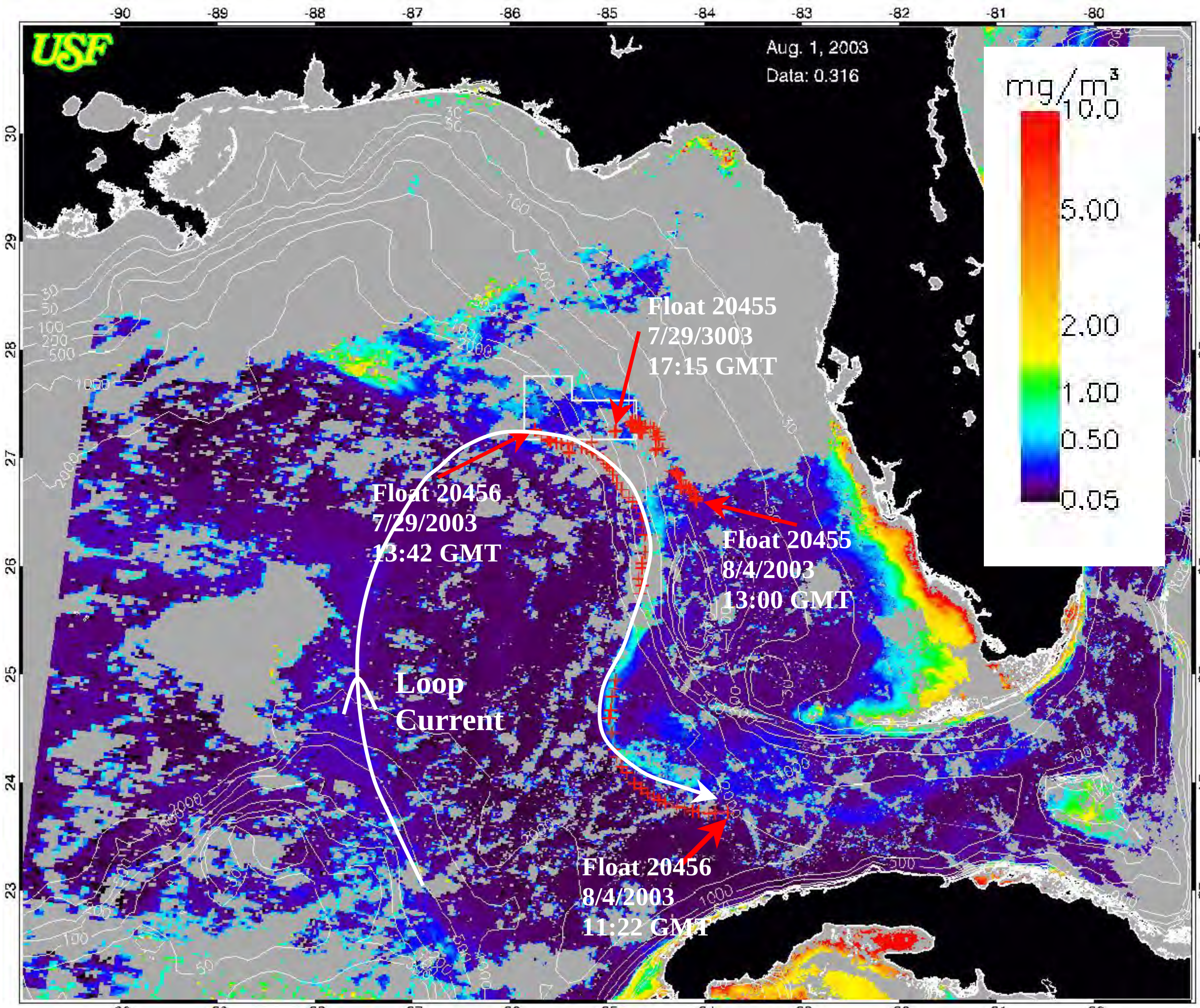


Figure 4. MODIS chlorophyll satellite image captured on 1 August 2003, when more than 16-million gallons of treated wastewater had been dispersed in the area outlined by the white box beginning on July 20th, 2003. The enhanced color south of the dispersal area is natural and results from biological activity along the edge of the Loop Current (the Loop Current entrained low chlorophyll concentration waters, as outlined on the image). Enhanced colors around cloud edges are algorithm artifacts. Overlaid on the image are the locations of two Argo floats (red crosses. Argo data courtesy of Jason Law and Robert Weisberg, USF) that flow with the currents. Also overlaid on the image are bathymetry (water depth) contour lines. The difference between the float position and the color patch position around 24^{o}N 84.5^{o}W is due to the southward movement of the water mass from 1 August (image date) and 4 August (float date). This effect is more apparent in Figure 5.

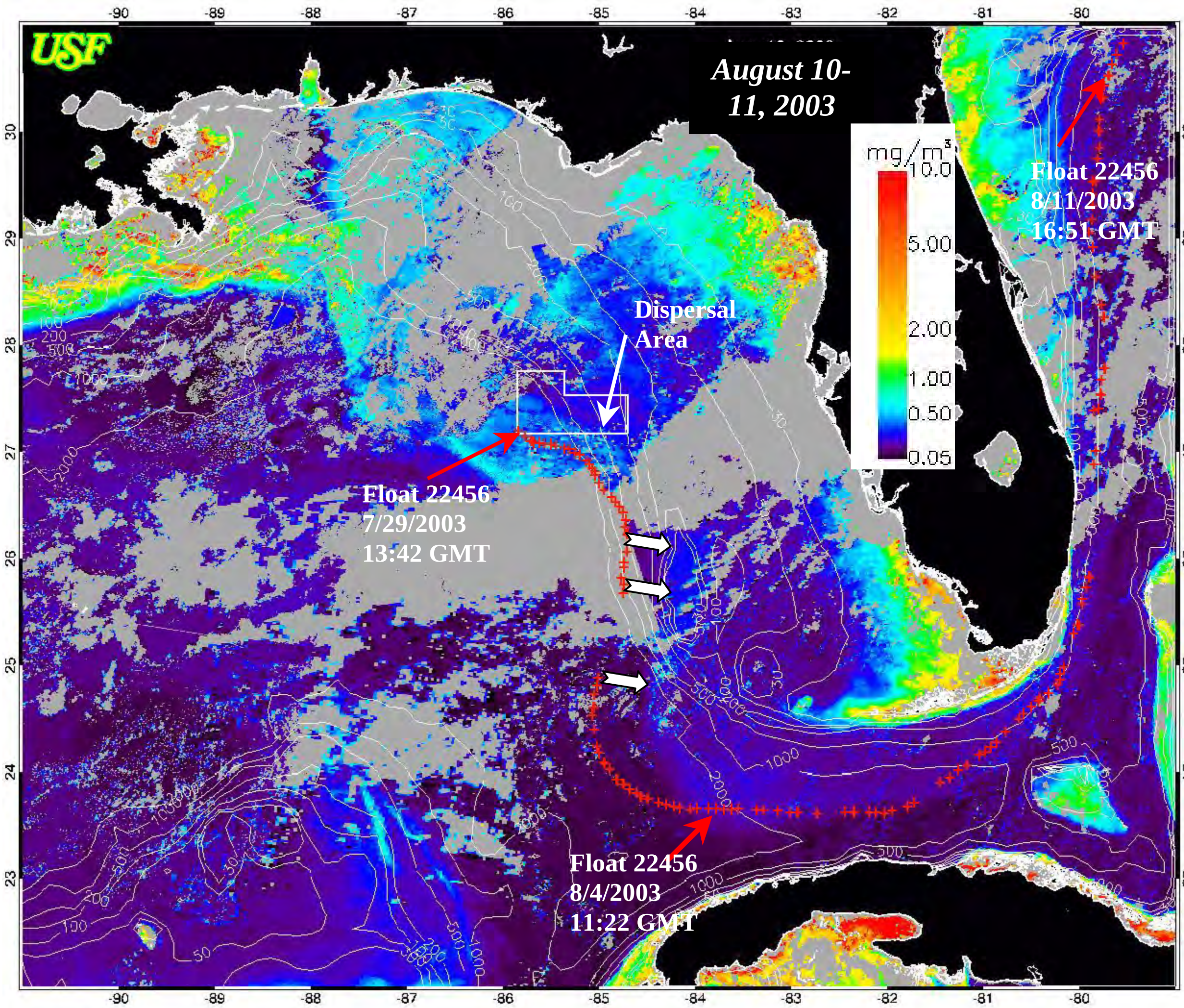


Figure 5. MODIS chlorophyll image for 10-11 August 2003, when about 27-million gallons of treated wastewater had been dispersed in the area outlined by the white box beginning on 20 July 2003. Overlaid on the image are the locations of one Argo drifter (red crosses. Argo data courtesy of Jason Law and Robert Weisberg, USF) that tracked currents. Difference between image and drifter dates is shown as a difference in the location of the drifter track and the edge of the Loop Current. This difference shows how far the edge of the LC moved toward Florida over a short period, in the direction indicated by the white arrows.

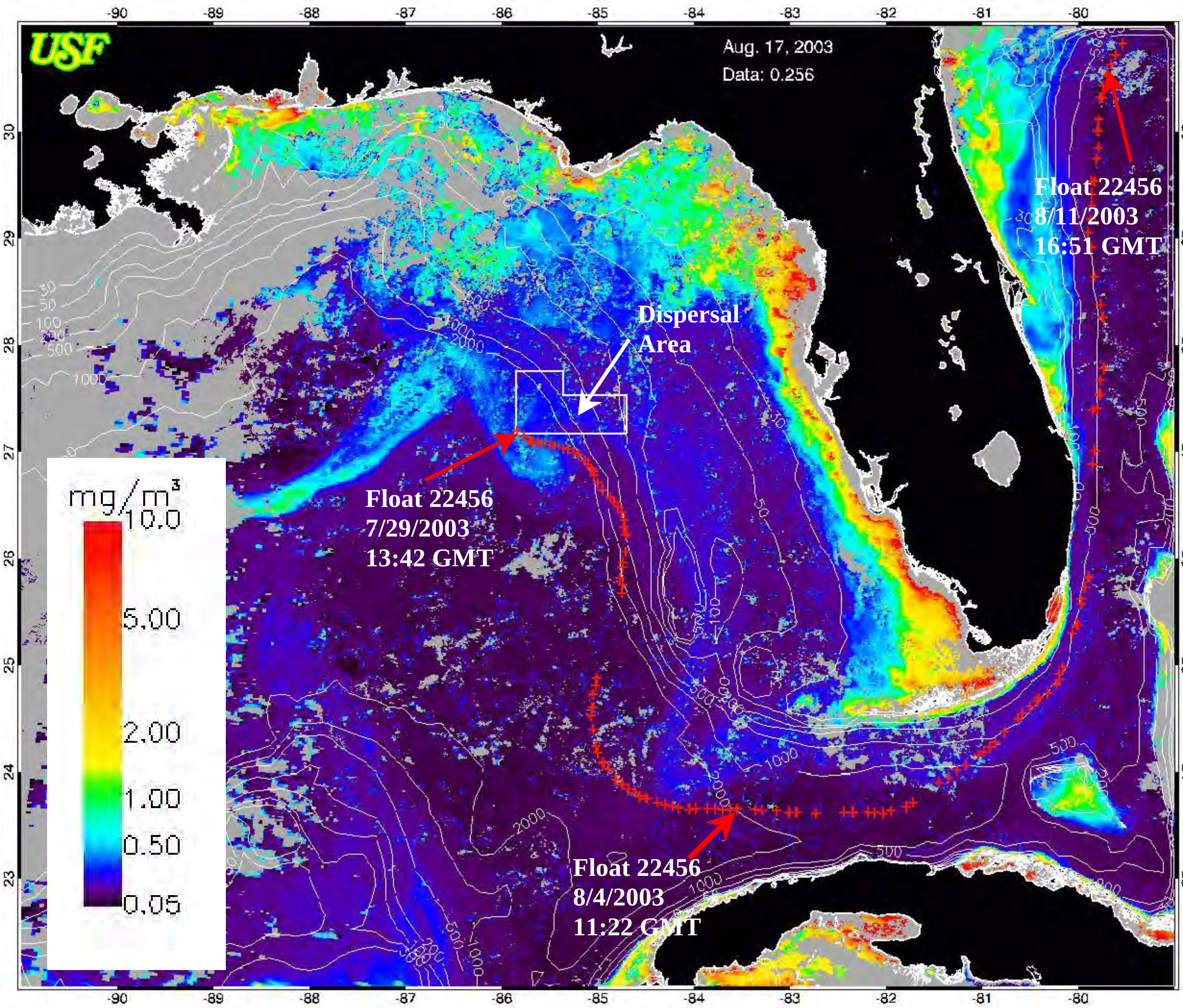


Figure 6. MODIS chlorophyll composite (11:53am and 3:02pm) satellite image for 17 August 2003, when about 40-million gallons of treated wastewater had been dispersed in the area outlined by the white box beginning on 20 July 2003. Overlaid on the image are the locations of one Argo float (red crosses. Argo data courtesy of Jason Law and Robert Weisberg, USF). Also overlaid on the image are bathymetry (water depth) contour lines. The color band tracing the edge of the Loop Current in the Florida Strait south of the Dry Tortugas moved to the north as compared to its position on 10-11 August (see Fig. 5).

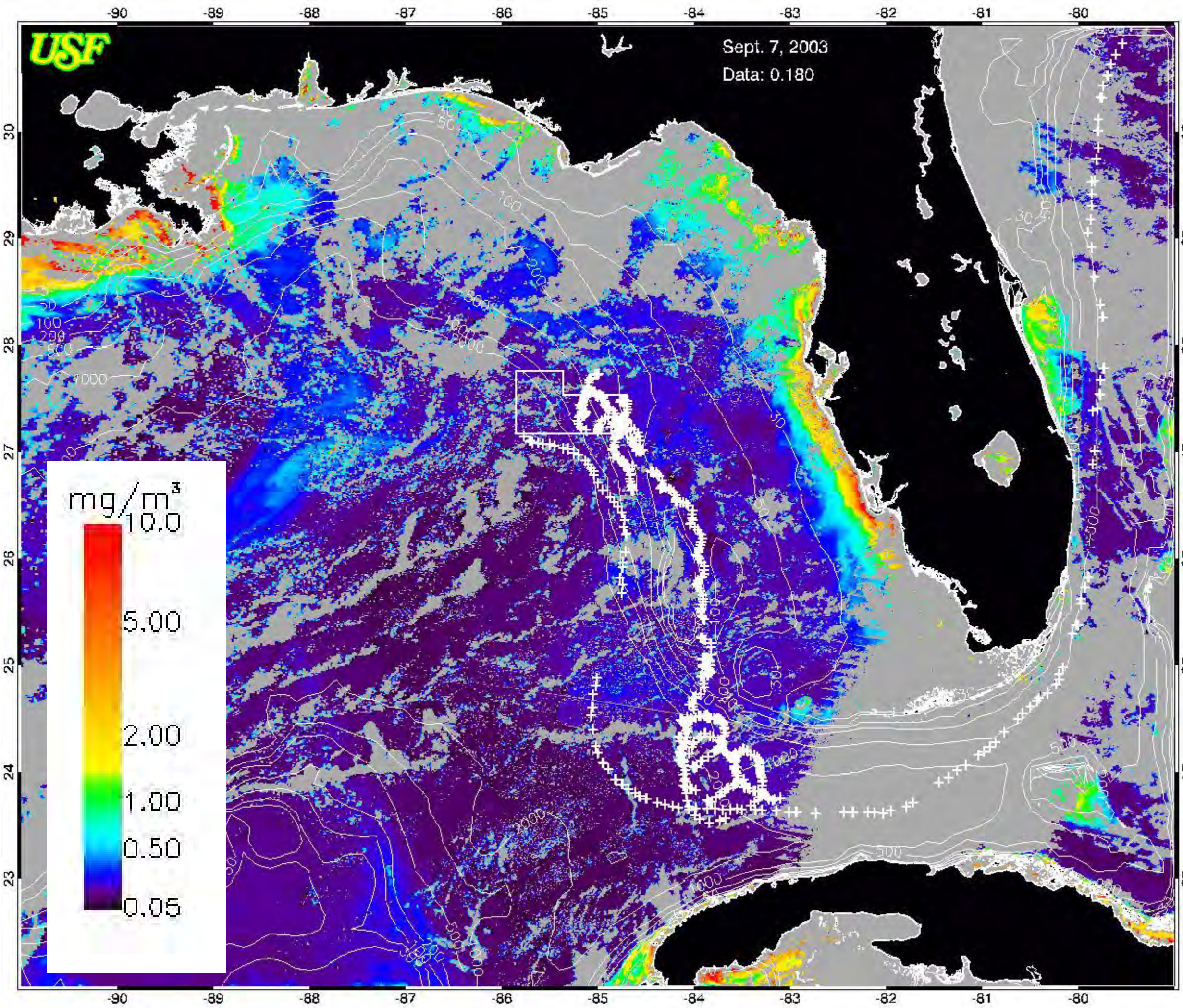


Figure 7. MODIS satellite-derived "chlorophyll" product for 7 September 2003. Overlaid on the image are the tracks of six Argo floats (white crosses. Argo data courtesy of Jason Law and Robert Weisberg, USF). These drifters show the general movement of water and currents from late July to early September 2003. Also overlaid on the image are bathymetry contour lines (water depth) and the outlines (white box) of the dispersal area. The color band along the eastern Loop Current edge becomes more diffused on the West Florida Shelf.

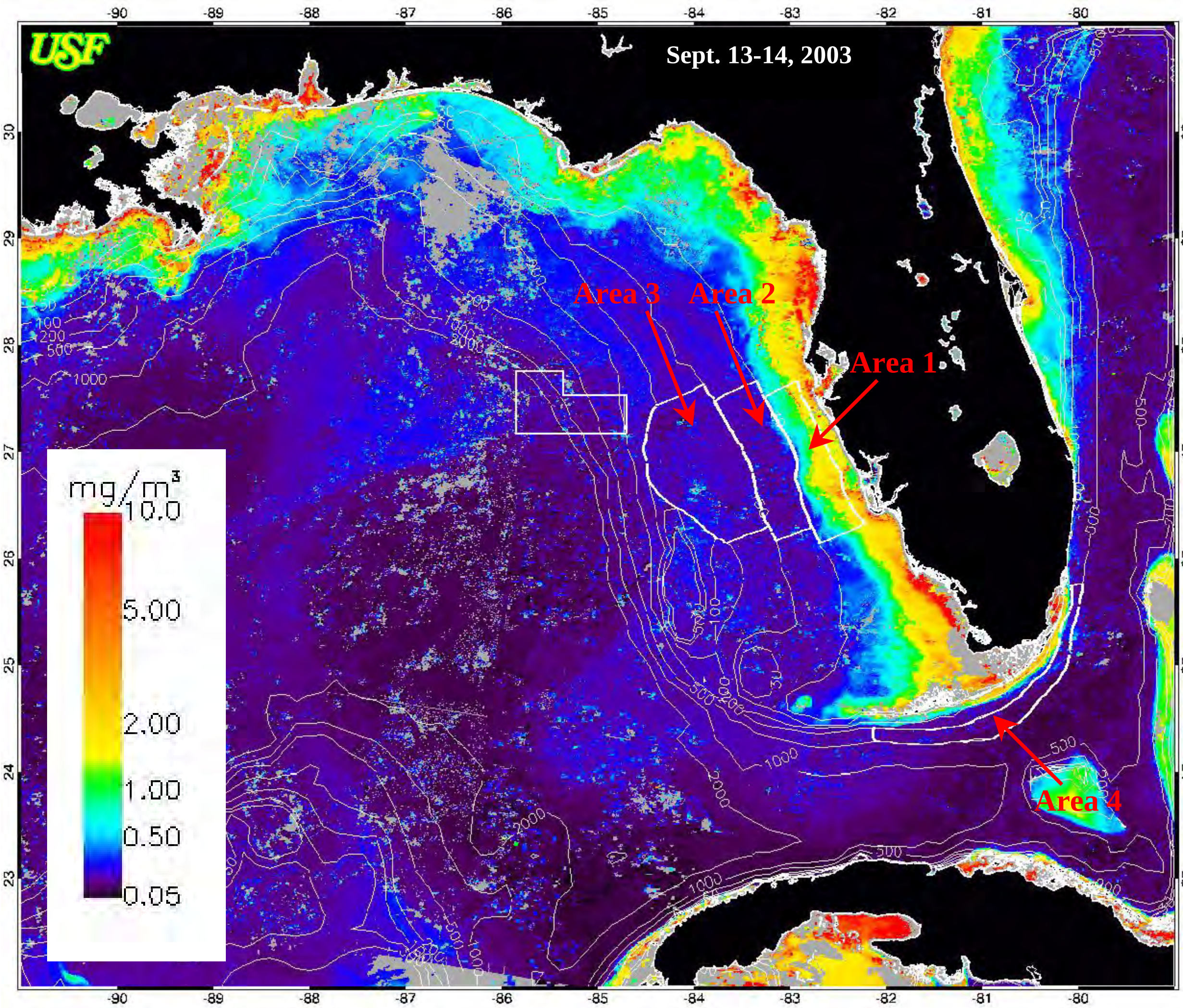


Figure 8. MODIS satellite-derived "chlorophyll" product for 13-14 September 2003. Overlaid on the image are bathymetry contour lines (water depth) and the outlines (white box) of the dispersal area. Areas 1 to 4 were selected to study long-term color changes over a period of seven years, to establish a baseline prior to the dispersal of Piney Point wastewater.

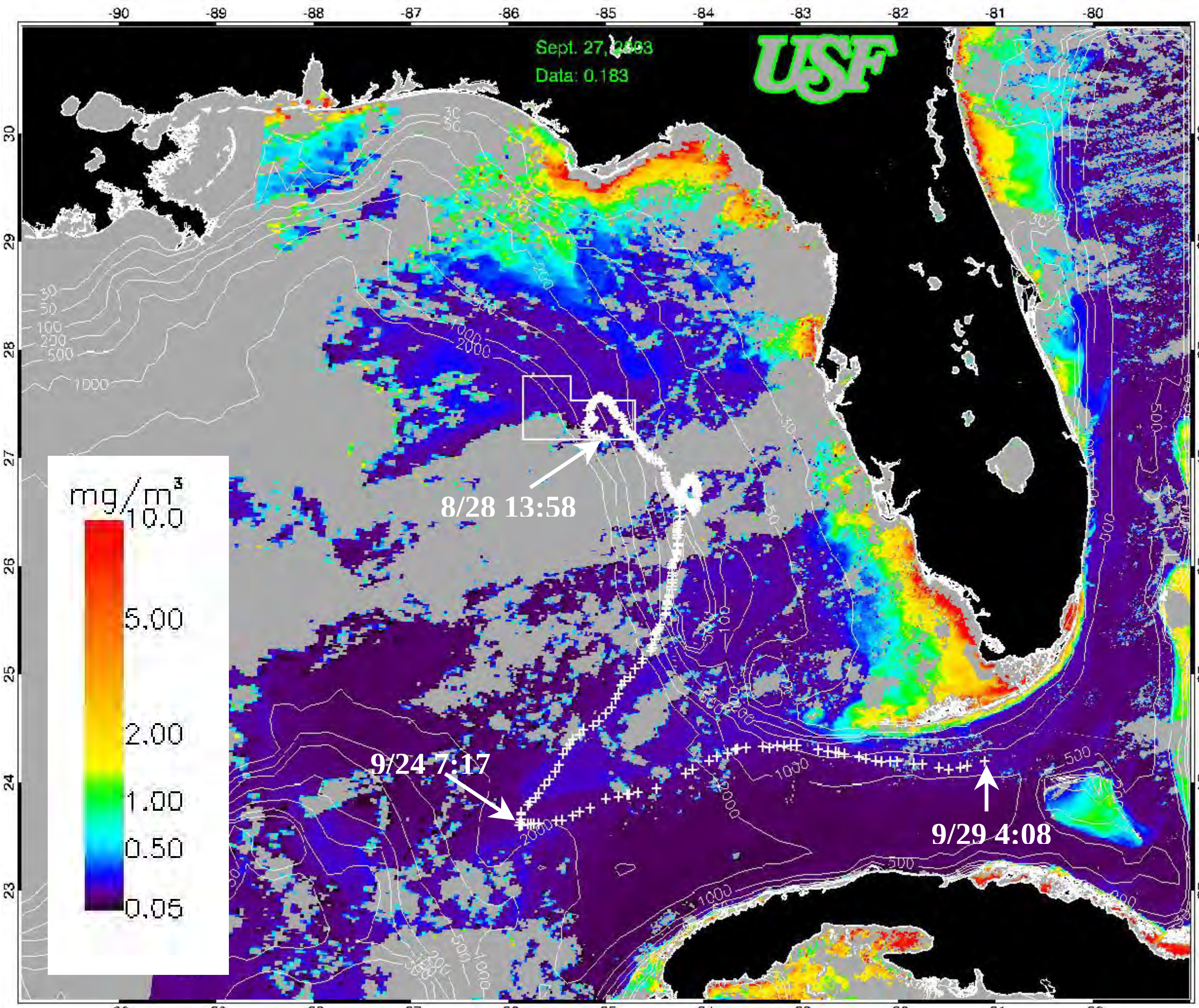


Figure 9. MODIS satellite-derived "chlorophyll" product for 27 September 2003. Overlaid on the image are the outlines (white box) of the dispersal area, the water depth contours (30 – 2000 m), and the flow tracks of a surface drifter (Argo #39764. data courtesy of Jason Law and Robert Weisberg, USF). A large eddy is being shed from the Loop Current.

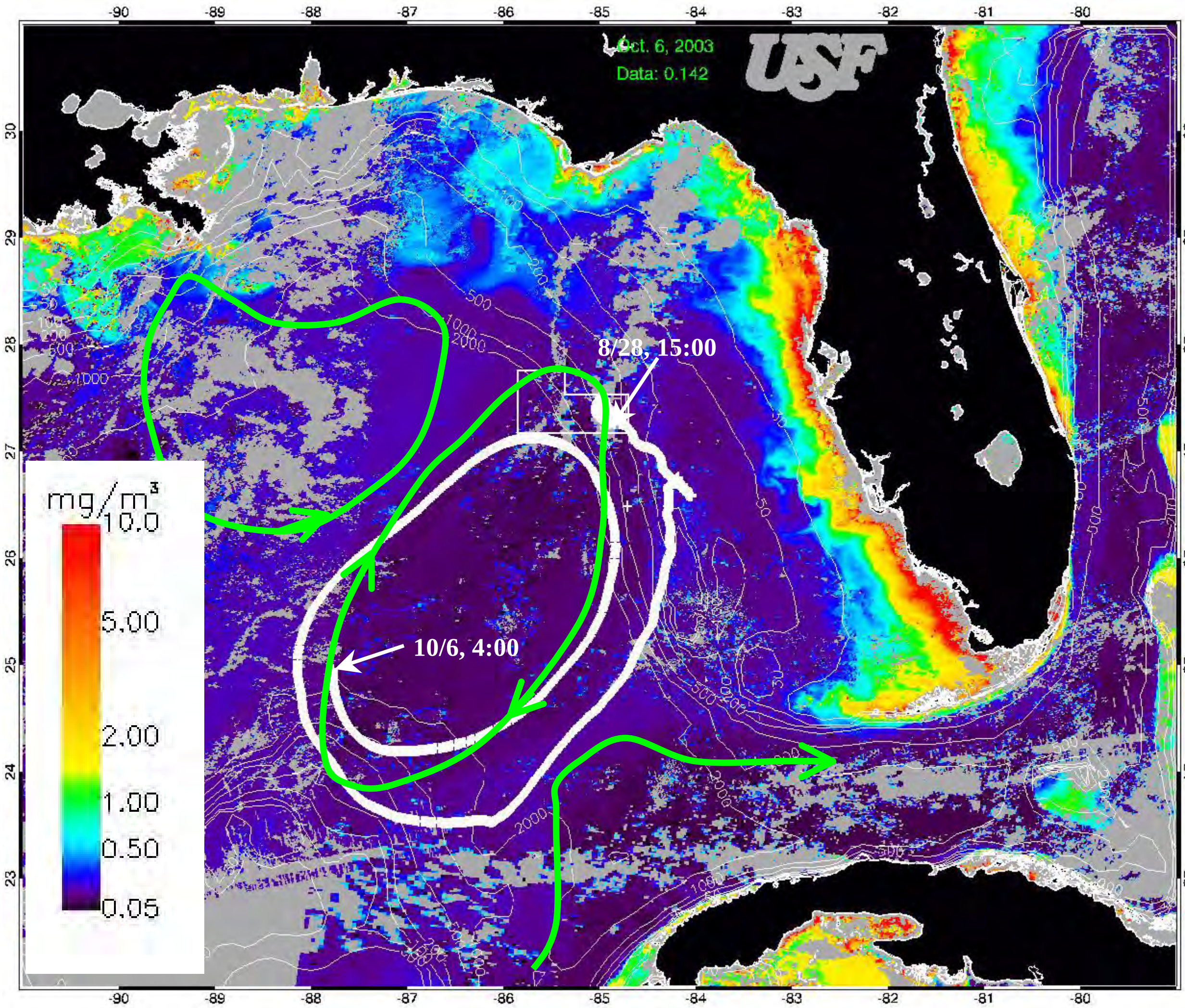


Figure 10. MODIS satellite-derived "chlorophyll" product for 6 October 2003. Overlaid on the image are the outlines (white box centered at about 27.2°N 85.5°W) of the dispersal area, the water depth contours (30 – 2000 m), the Loop Current pathway, and a pair of anti-cyclonic (clockwise) and cyclonic (counter-clockwise) eddies. Green lines with arrows are manually drawn based on ocean color data only but are consistent with satellite altimeter data. The water movement tracks detected by Argo float # 20089 (data courtesy of Jason Law and Robert Weisberg, USF) are shown as white spiraling lines.

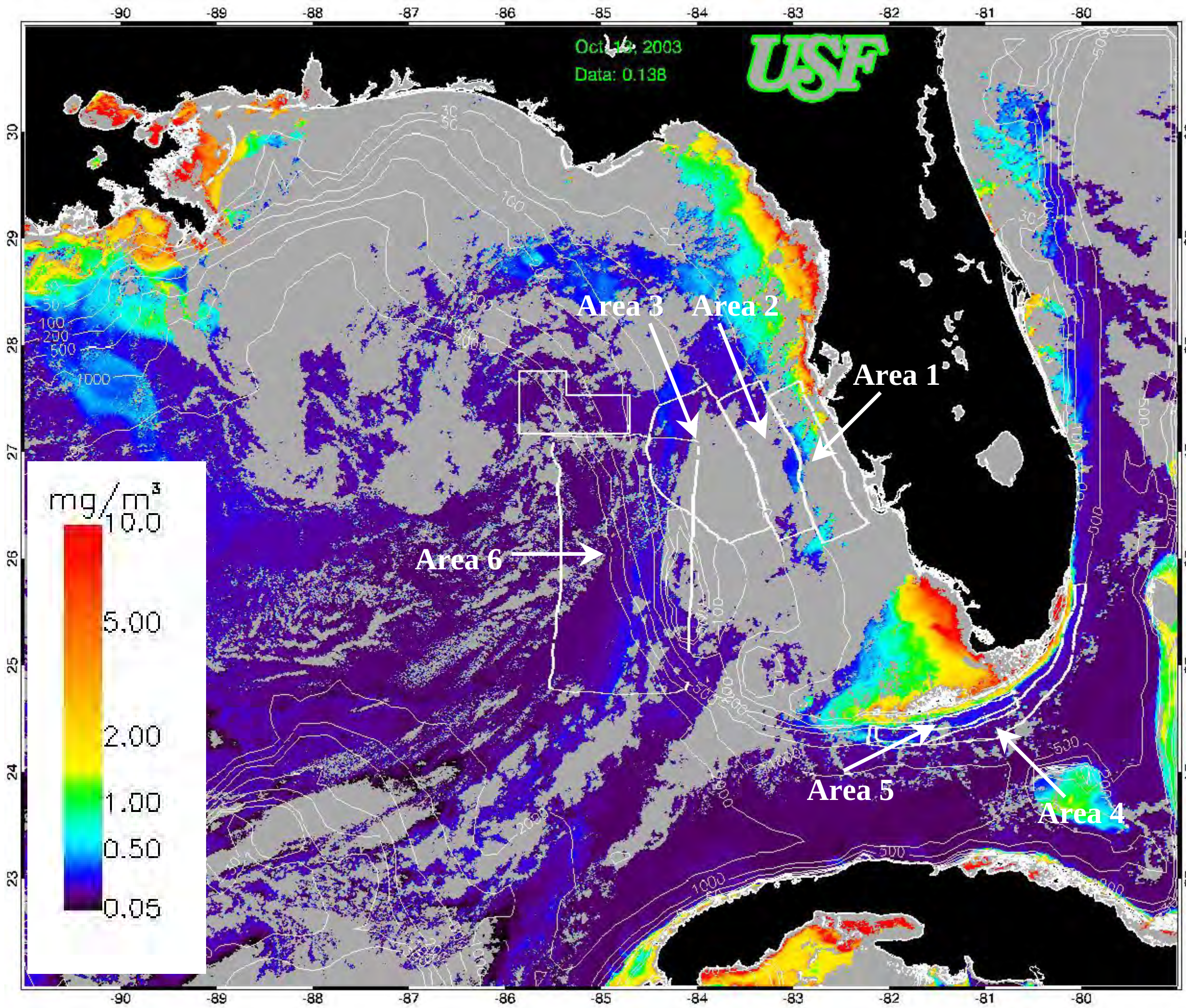


Figure 11. MODIS satellite-derived "chlorophyll" product for 13 October 2003. Six areas are chosen to study the color changes through time. See text for details.

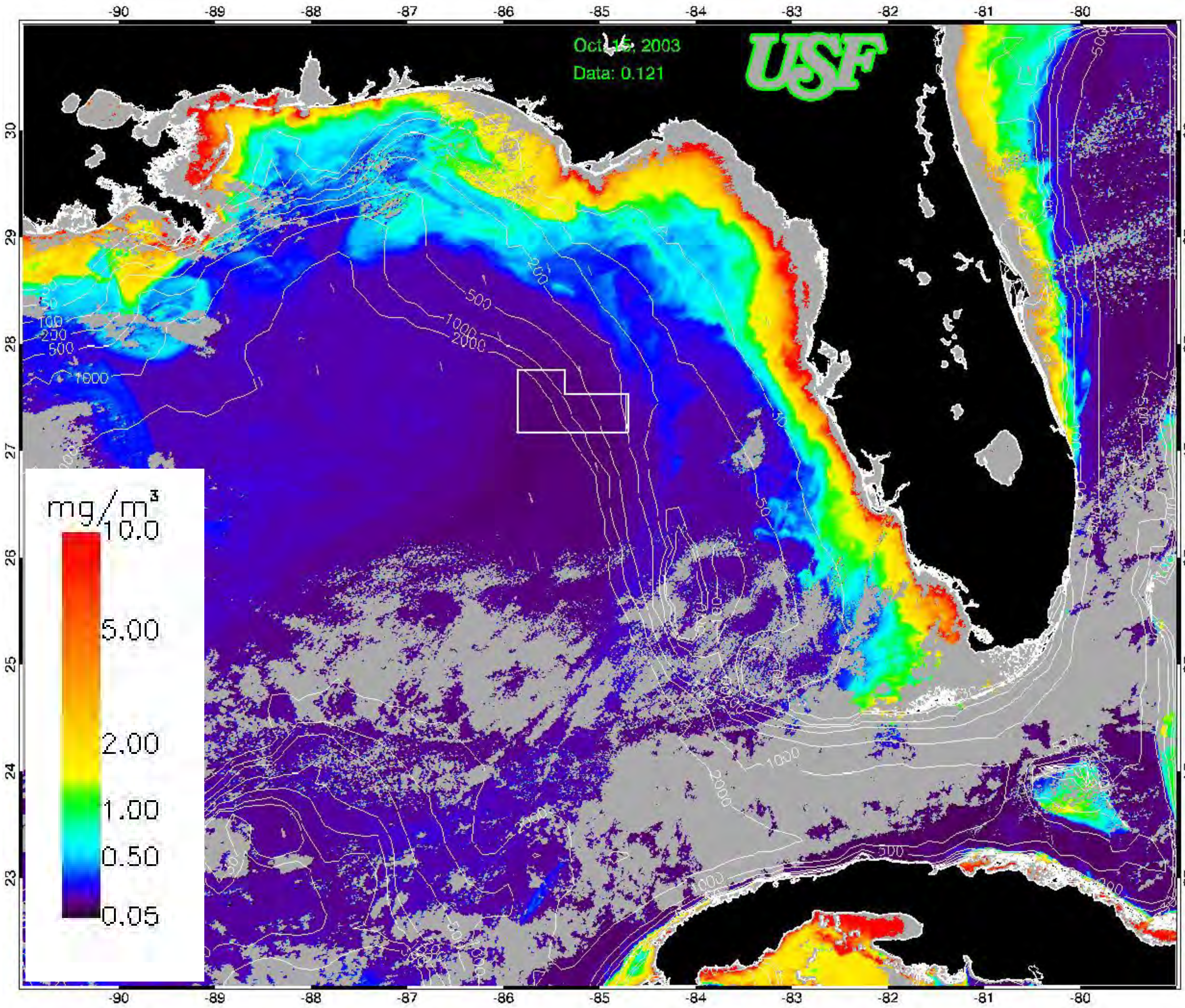


Figure 12. MODIS satellite-derived "chlorophyll" product for 15 October 2003, 18:44 GMT. Overlaid on the image are the outlines (white box centered at about 27.2°N 85.5°W) of the dispersal area and the water depth contours (30 – 2000 m).

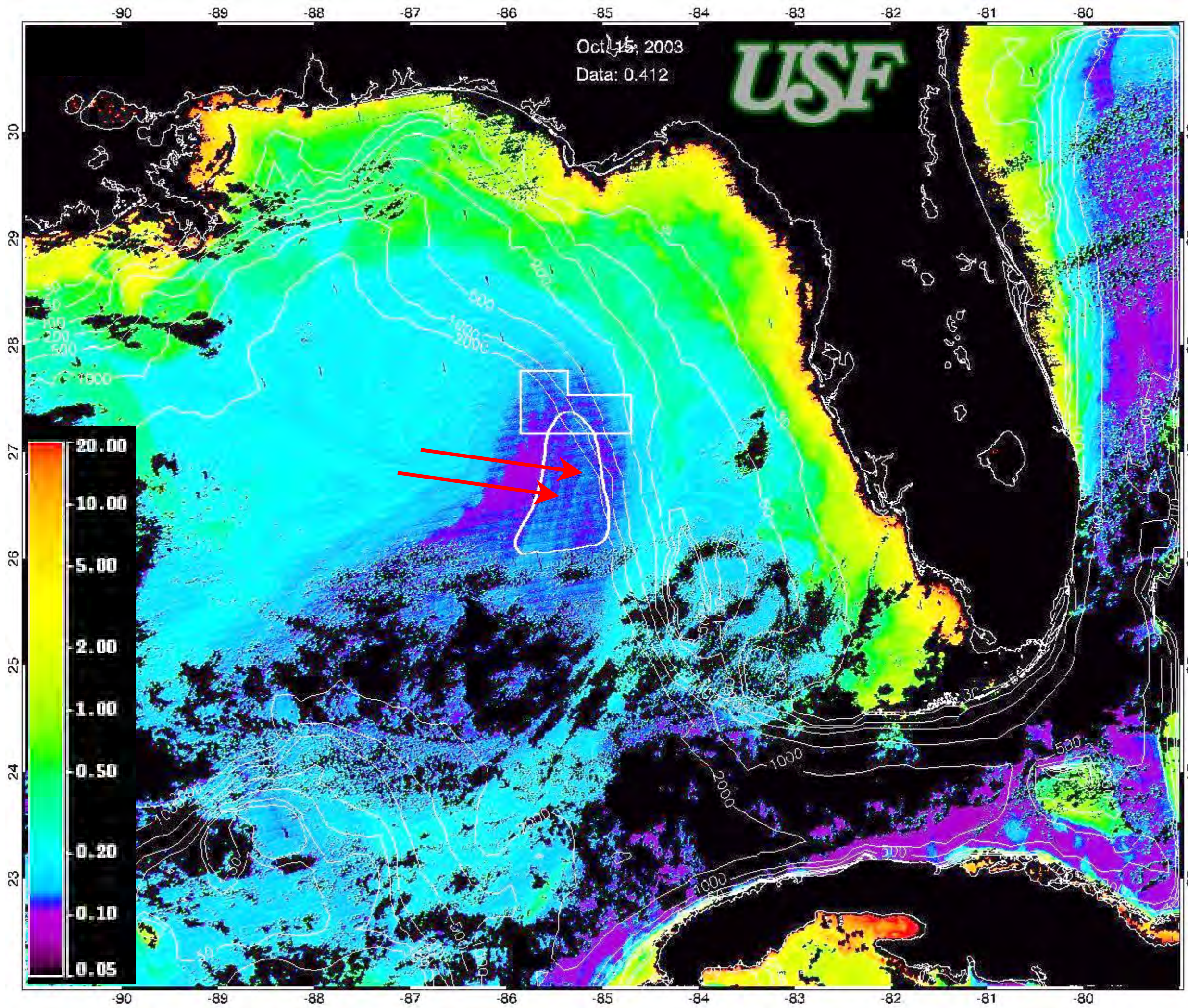


Figure 13. Same as Fig. 12 (15 October 2003, 18:44 GMT), but colors are stretched to show contrast at low concentrations. Slightly elevated chlorophyll "streamers" south of the dispersal area are indicated by the red arrows. It is not clear whether these are caused by local upward mixing of deep water, or whether they were associated with the Piney Point discharge from the 10-11 October 2003 barge operation. Deeper mixing that brings the bottom nutrient to the surface might have occurred at the edge of the eddy.

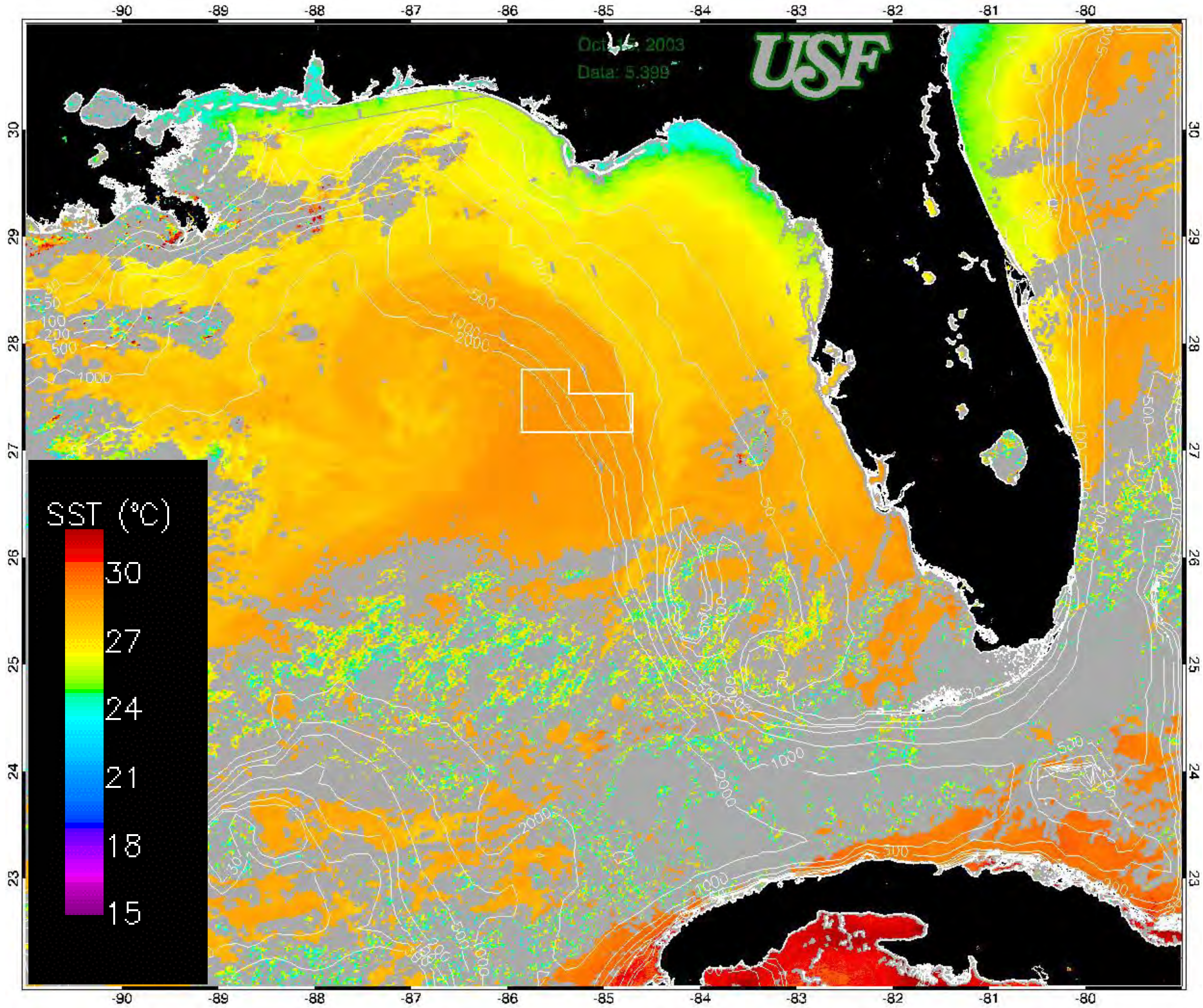


Figure 14. MODIS satellite-derived Sea Surface Temperature (SST) for 15 October 2003, 18:44 GMT (same satellite overpass as for Figs. 12 and 13).

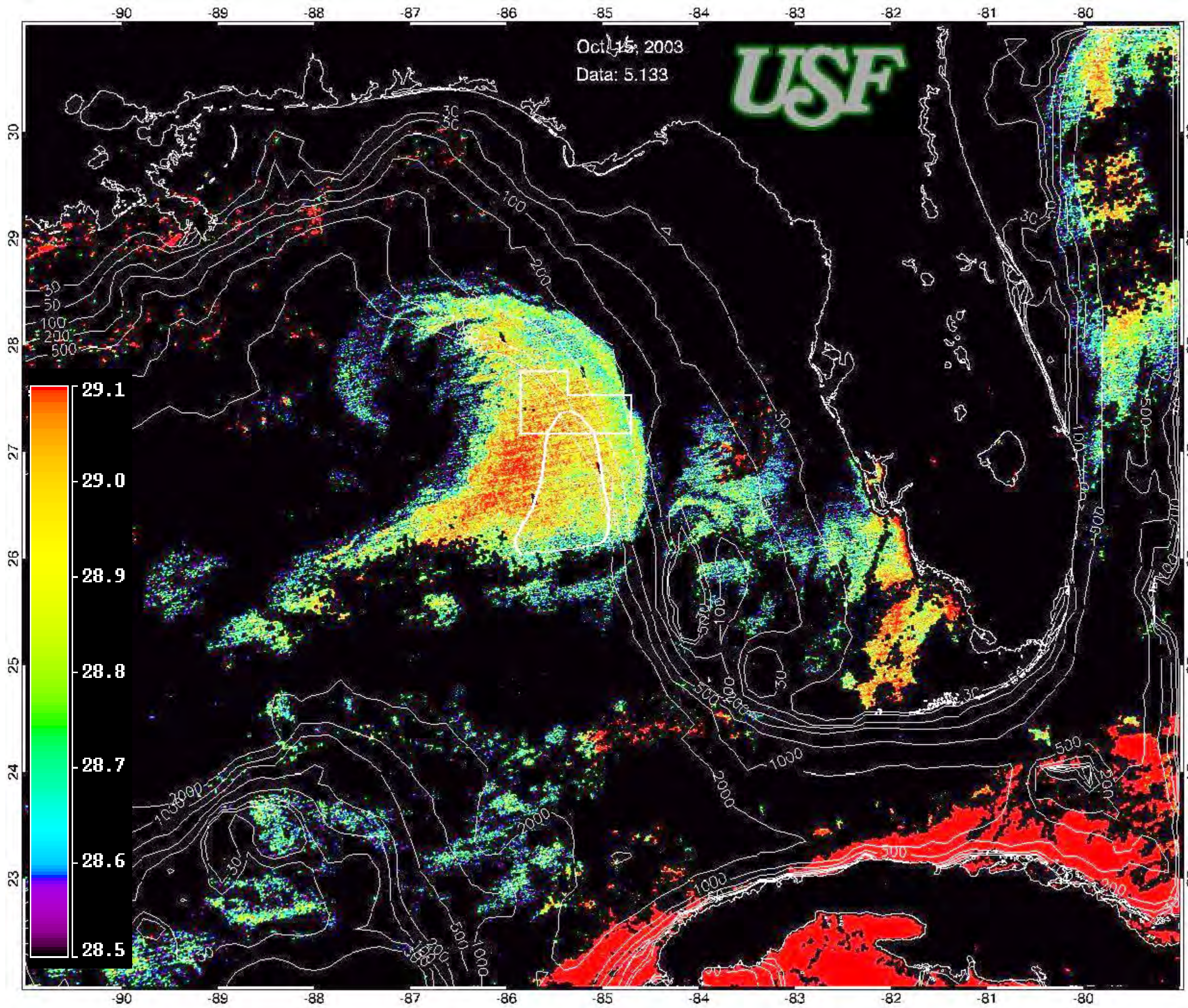


Figure 15. Same as Fig. 14, but colors are stretched to show contrast for SST range 28.5^{o}C to 29.1^{o}C. There is slight (0.1 – 0.2^{o}C) SST drop in the area where chlorophyll "streamers" are found. Deeper mixing with the bottom cold water might have occurred.

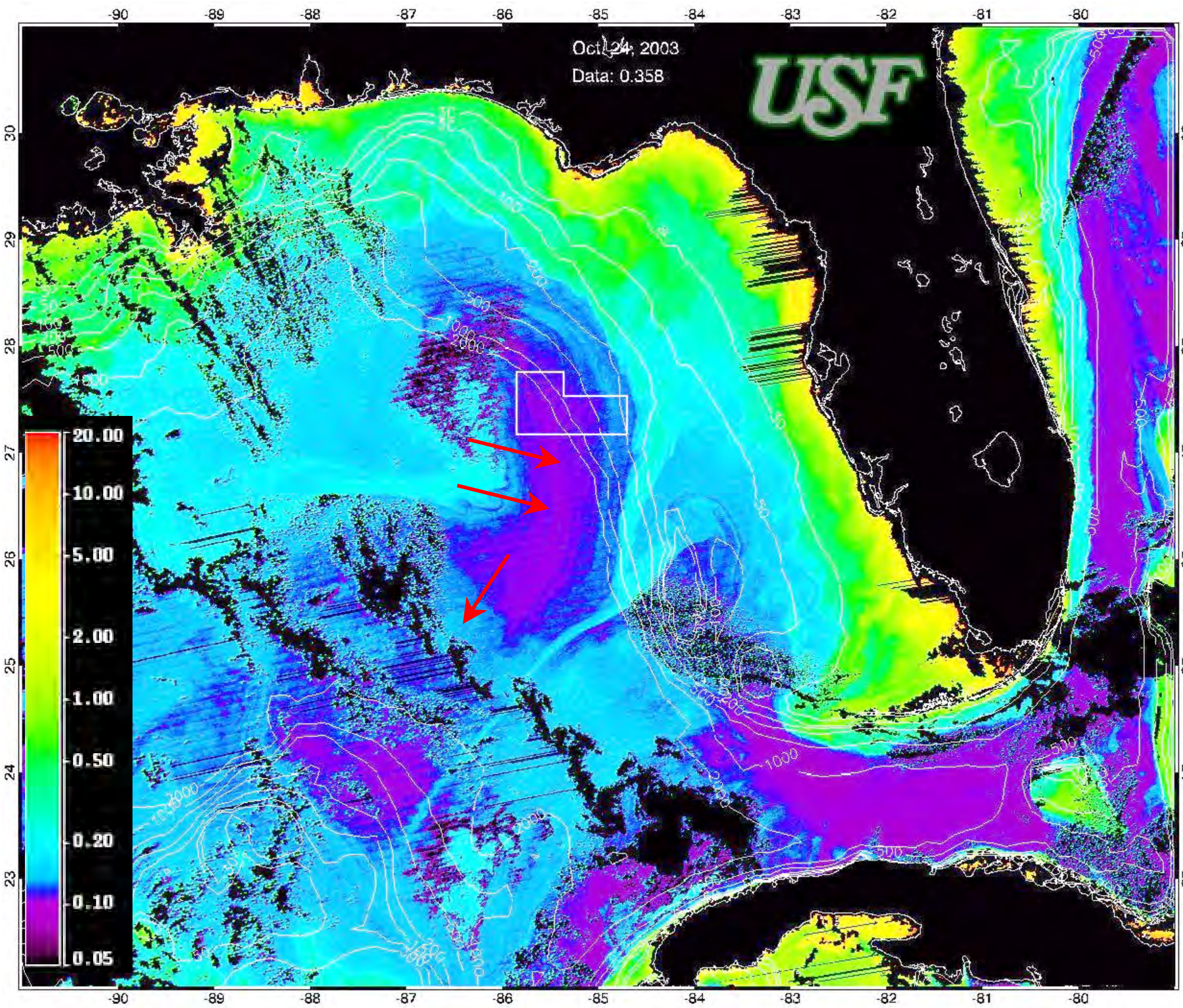


Figure 16. MODIS satellite-derived "chlorophyll" product for 24 October 2003, 18:38 GMT. The colors are stretched to show contrast at low concentrations. Slightly elevated chlorophyll streamers south of the dispersal area are indicated by the red arrows. The colored patch in the lower half of the eddy (annotated by the red arrow) is apparently from deep mixing, as indicated by the slight drop (0.1 – 0.4°C) in SST (see Fig. 17).

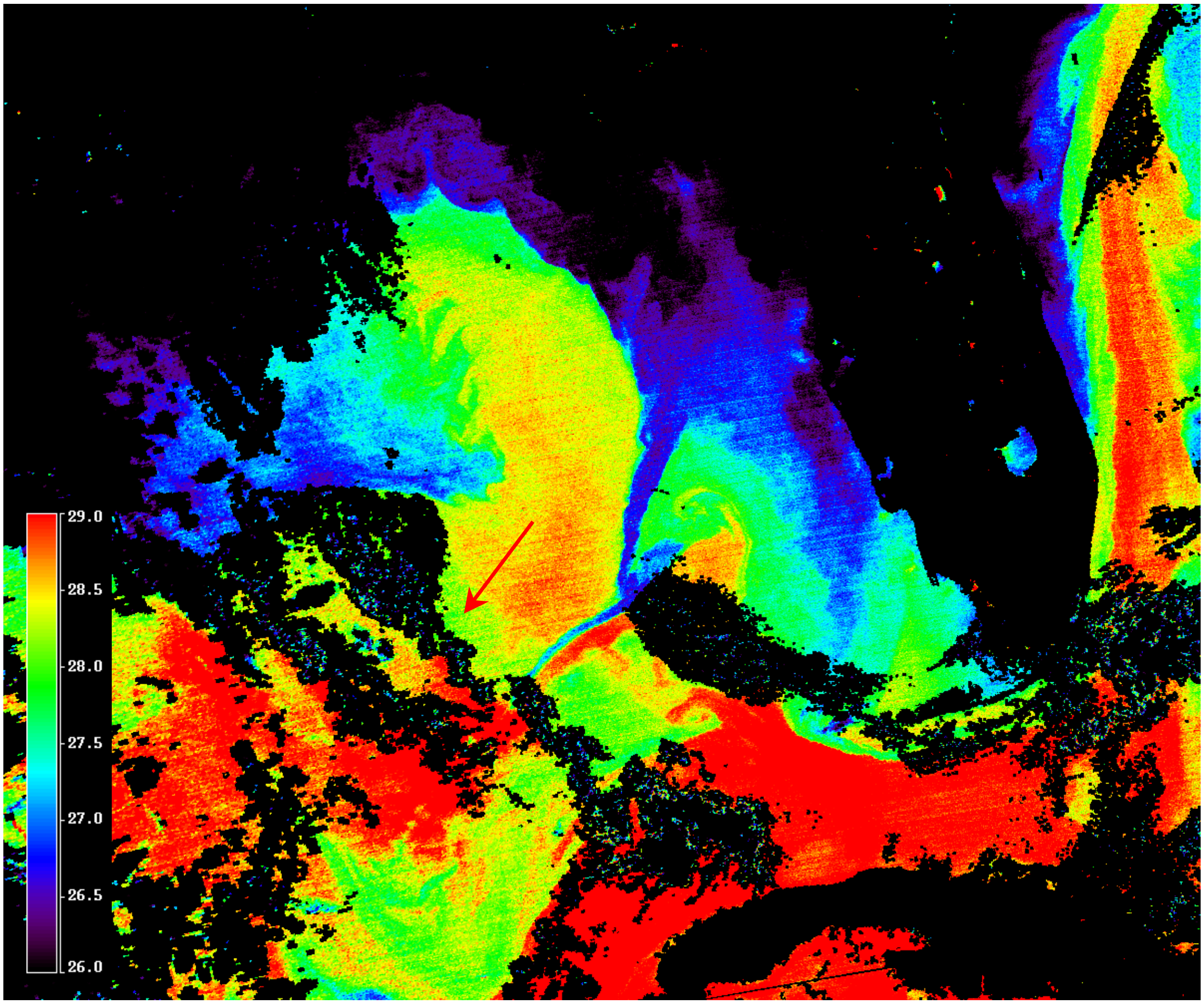


Figure 17. MODIS-derived SST image on 24 October 2003, 18:38 GMT (same satellite overpass as in Fig. 16). The colors are stretched to show contrast for SST range 26^{o}C to 29^{o}C. There is slight (0.1 – 0.4^{o}C) SST drop (annotated by the red arrow) in the area where elevated chlorophyll patch is found (see Fig. 16). Deeper mixing with the bottom cold, nutrient-rich water may have occurred.

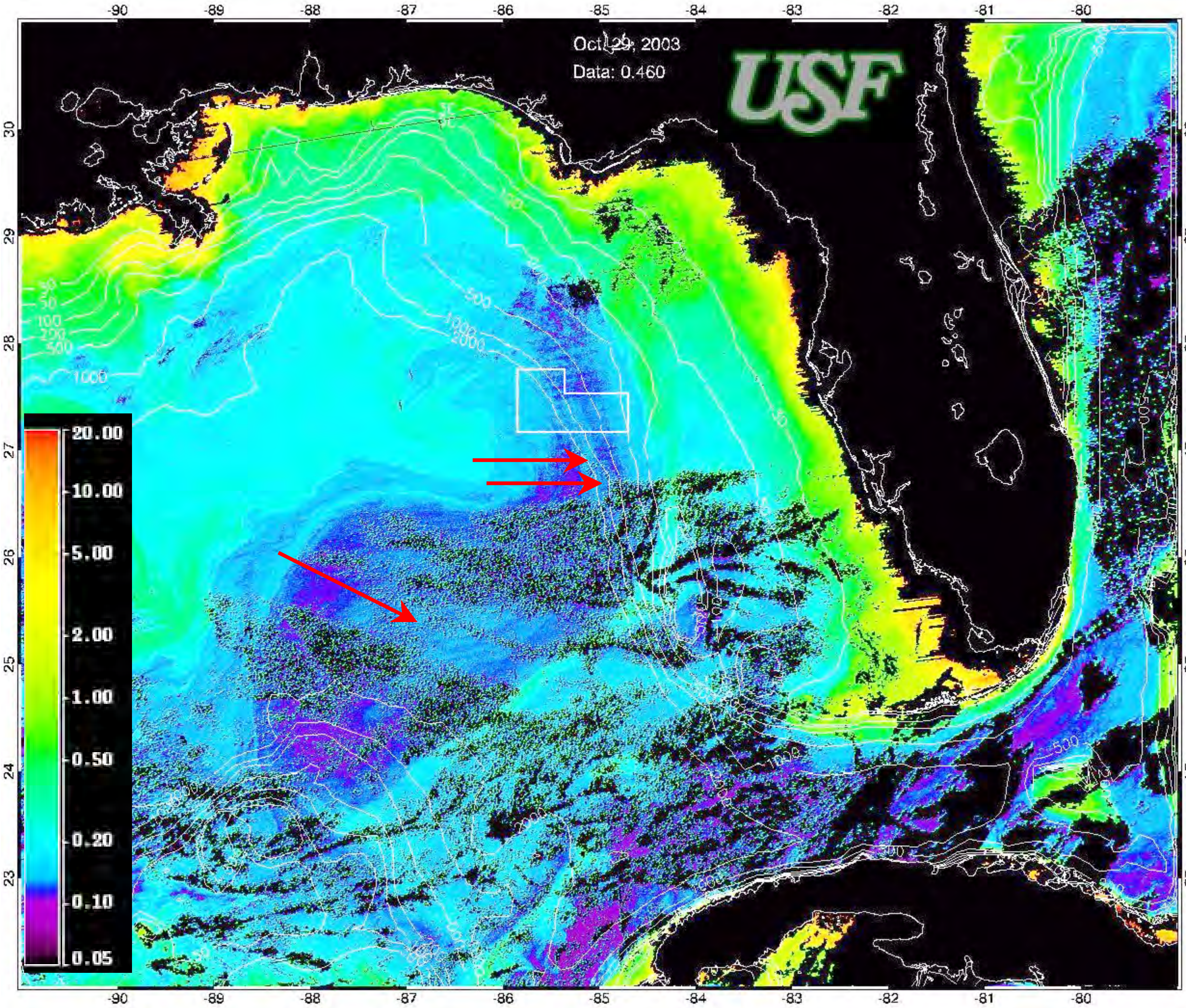


Figure 18. . MODIS satellite-derived "chlorophyll" product for 29 October 2003, 18:56 GMT, The colors are stretched to show contrast at low concentrations. The red arrows indicate slightly elevated chlorophyll streamers south of the dispersal area. The discharged water might have contributed partially to these streamers. In the center of the eddy there is a large patch with elevated chlorophyll (annotated by the red arrow)

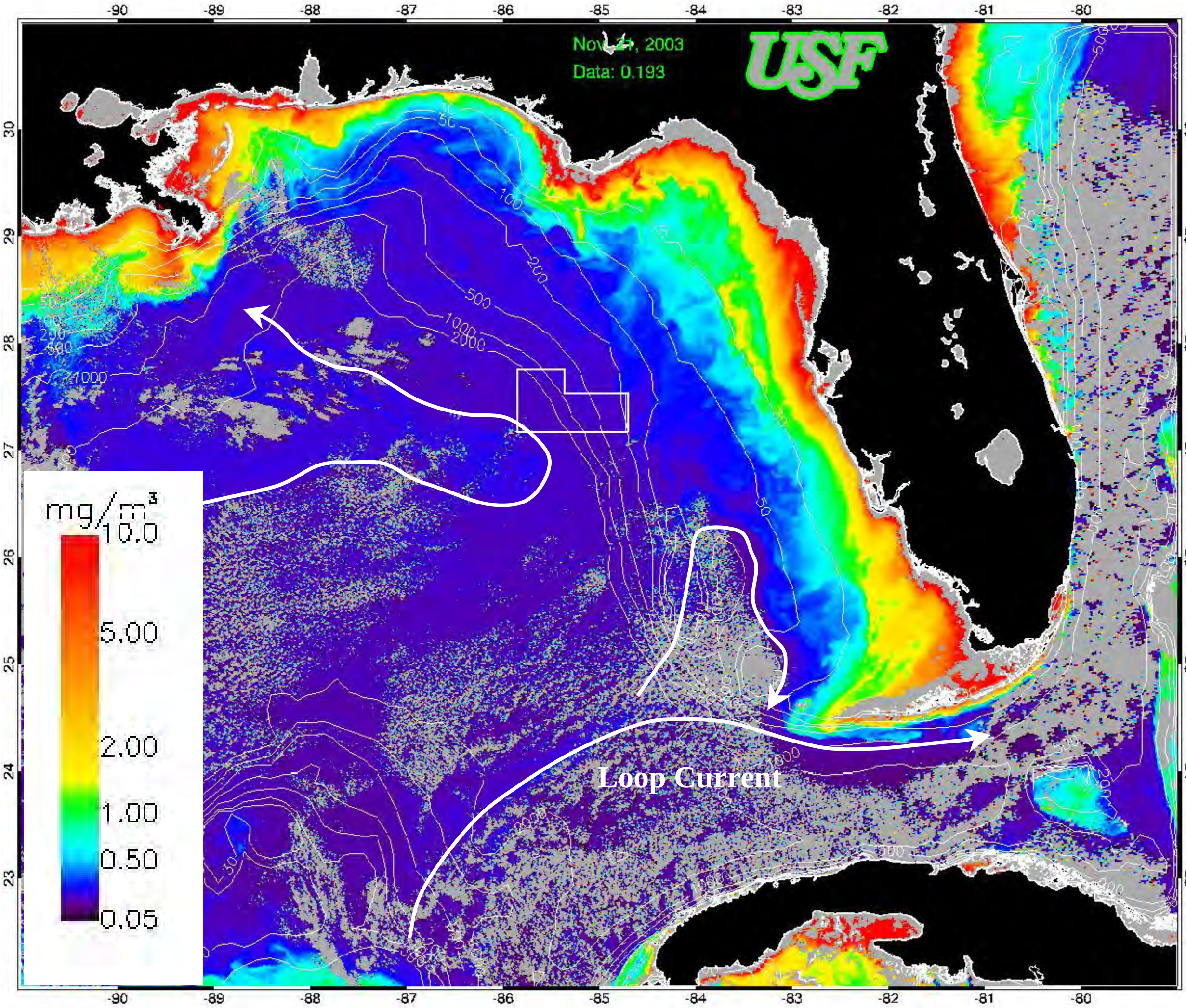


Figure 19. MODIS satellite-derived "chlorophyll" product for 21 November 2003, 19:06 GMT. Overlaid on the image are the outlines (white box centered at about 27.2°N 85.5°W) of the dispersal area and the water depth contours (30 – 2000 m).

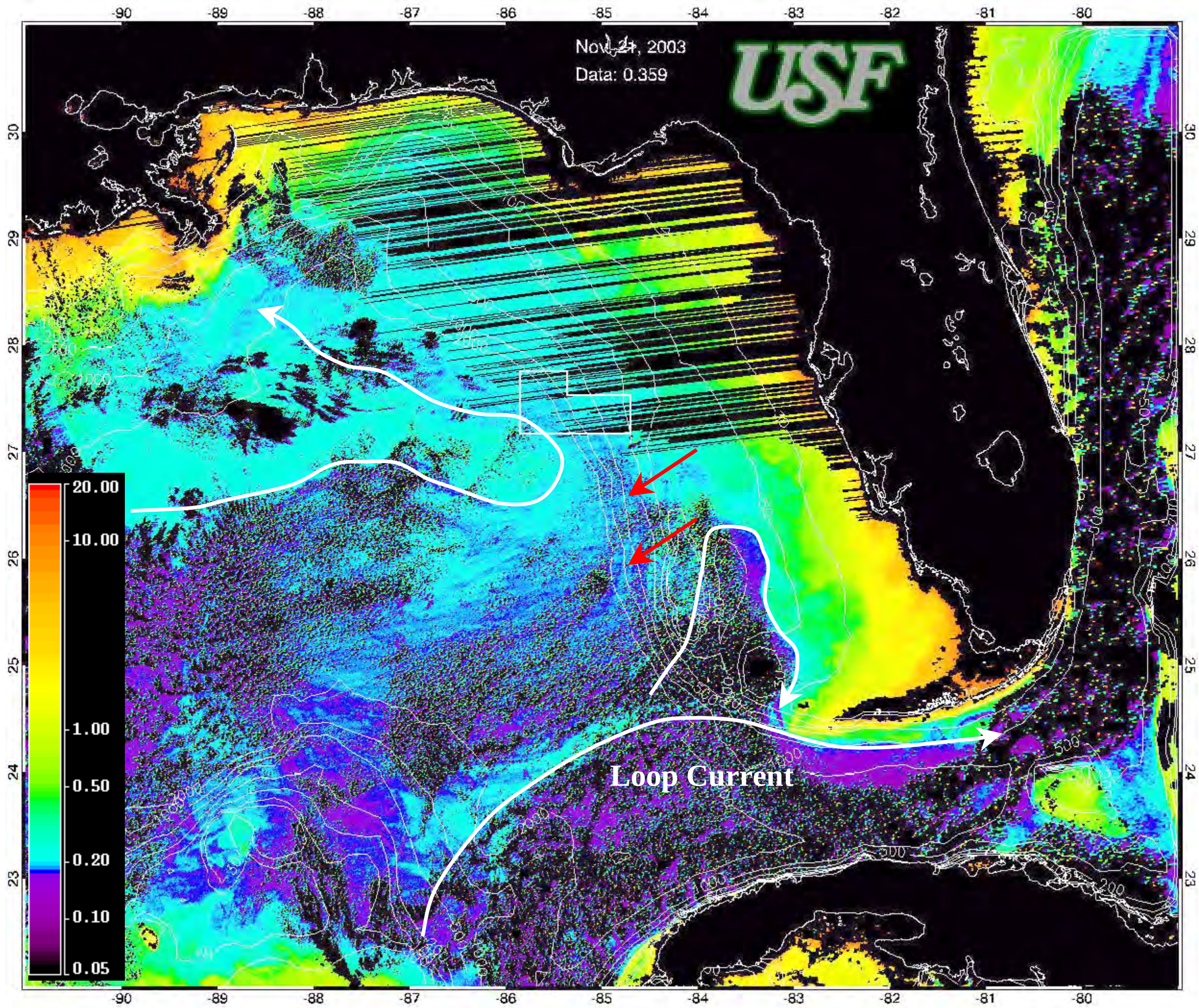


Figure 20. Same as Fig. 19 (21 November 2003, 19:06 GMT), but colors are stretched to show contrast at low concentrations. Note that to show better contrast the colors are stretched differently from those in Figs. 13, 16, and 18. Several enhanced chlorophyll "streamers" downstream of the discharge area (white box) are annotated with red arrows.

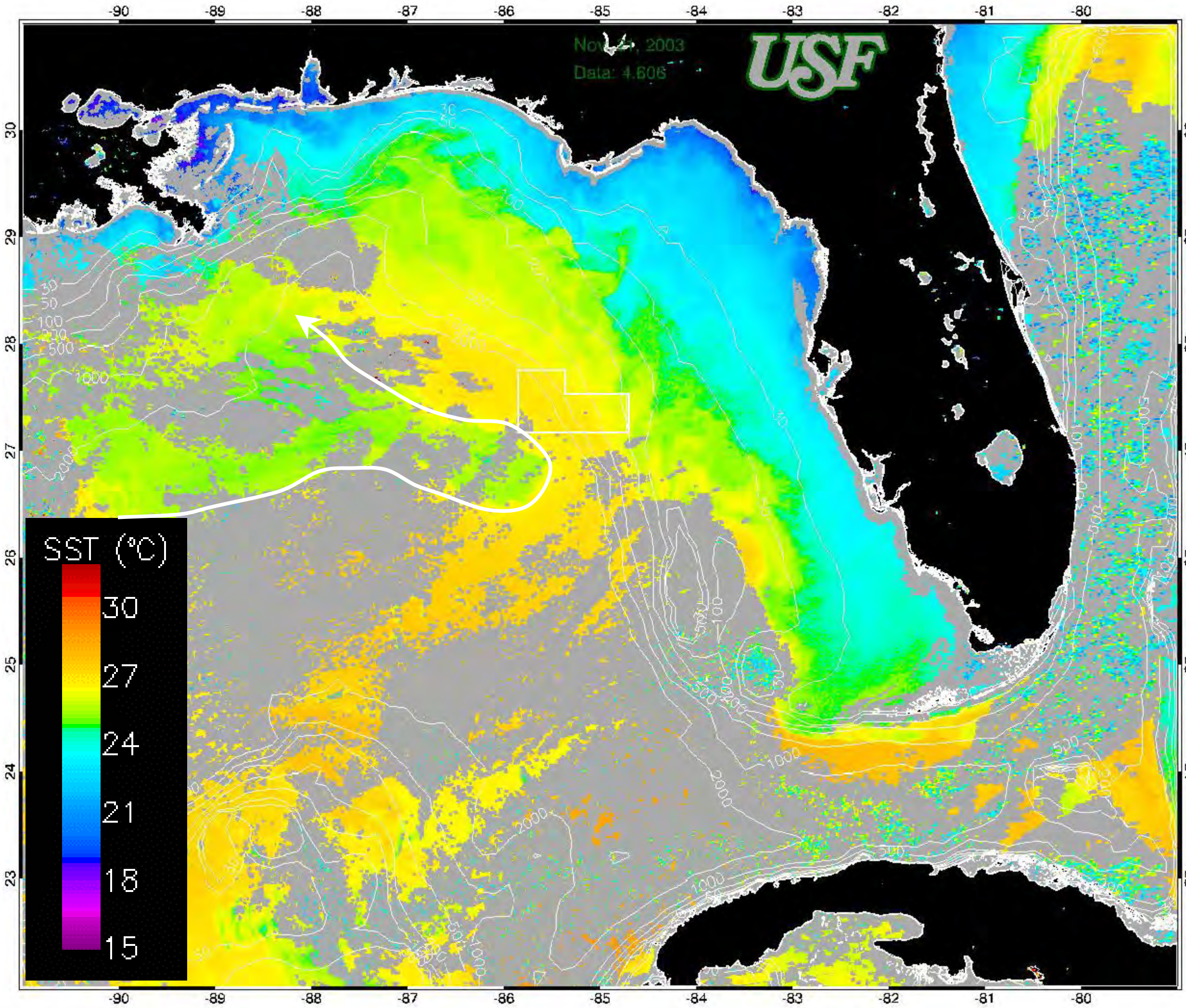


Figure 21. MODIS satellite-derived Sea Surface Temperature (SST) for 21 November 2003, 19:06 GMT (same satellite pass as in Fig. 20). Blue and green colors on top of clouds (gray color) should be treated as image noise.

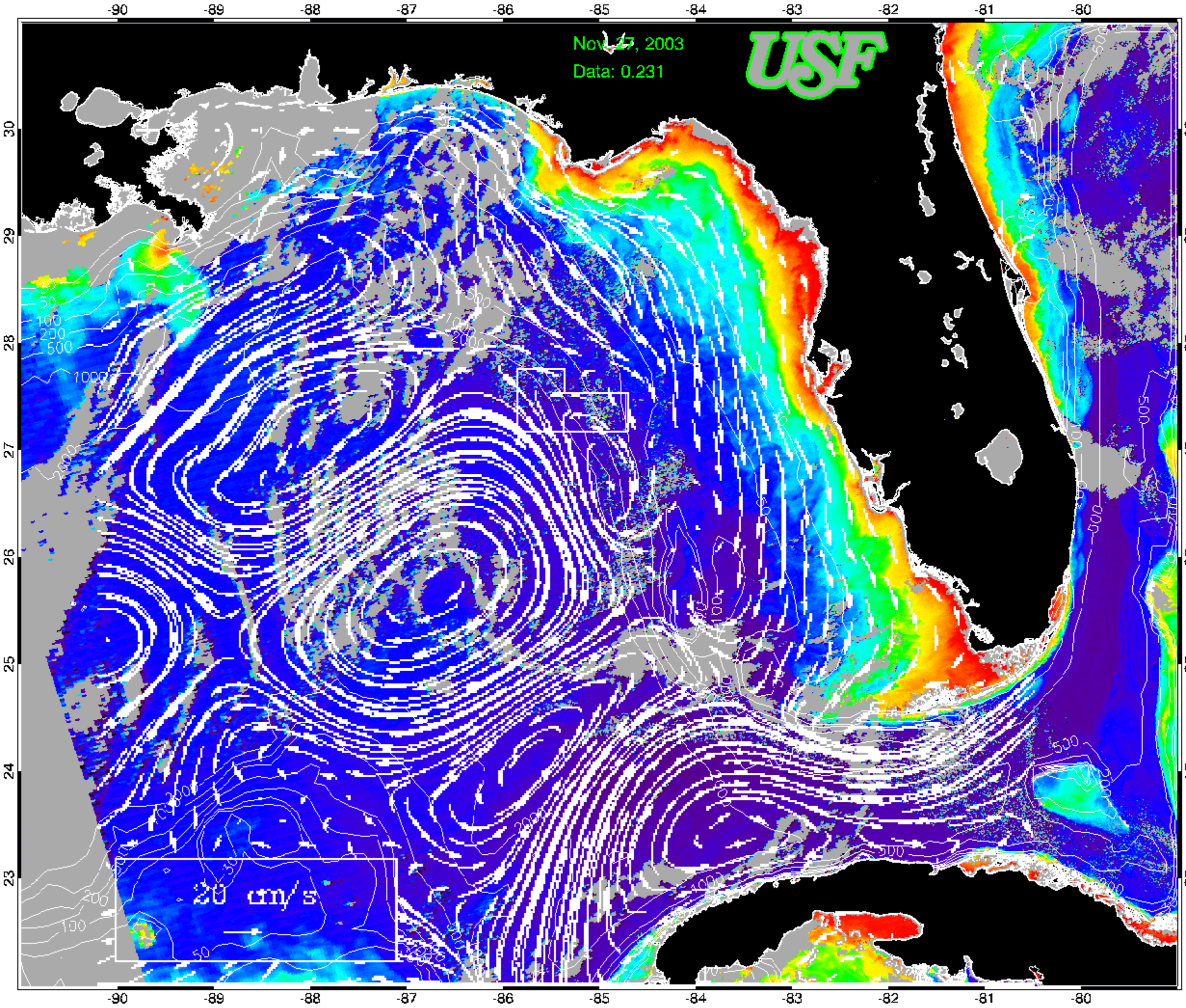


Figure 22. . MODIS satellite-derived "chlorophyll" image for 27 November 2003, 18:26 GMT, overlaid with current vectors (white arrows) derived from a numerical model (data courtesy of Naval Research Lab at Stennis, http://www7320.nrlssc.navy.mil/IASNFS_WWW/today/).

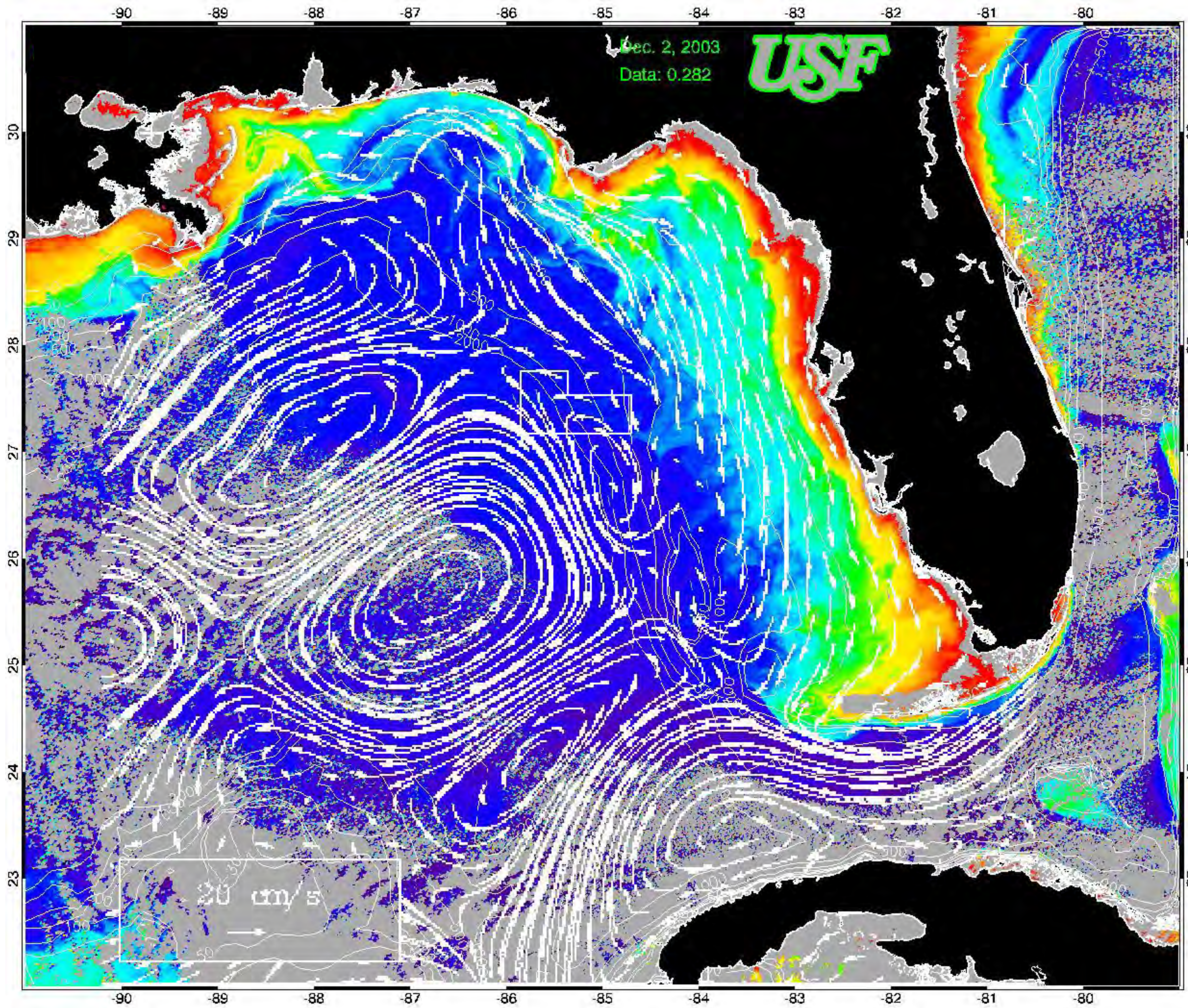


Figure 23. . MODIS satellite-derived "chlorophyll" image for 2 December 2003, 18:47 GMT, overlaid with current vectors (white arrows) derived from a numerical model (data courtesy of Naval Research Lab at Stennis, http://www7320.nrlssc.navy.mil/IASNFS_WWW/today/).

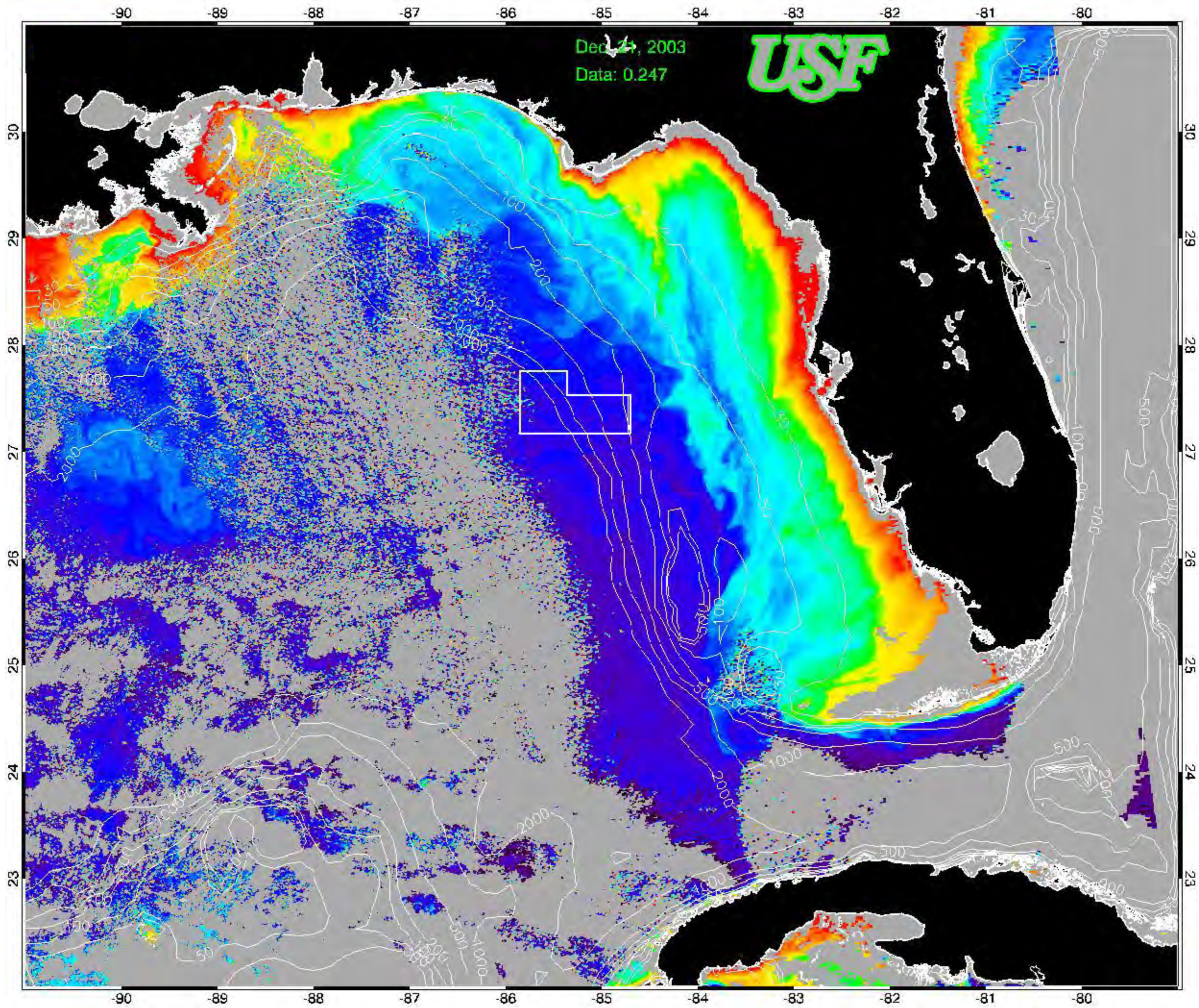


Figure 24. . MODIS satellite-derived "chlorophyll" image for 21 December 2003, 19:18 GMT. Overlaid on the image are water depth (bathymetry) contours from 30 to 2000 m, and the location (white box) of the dispersal area.

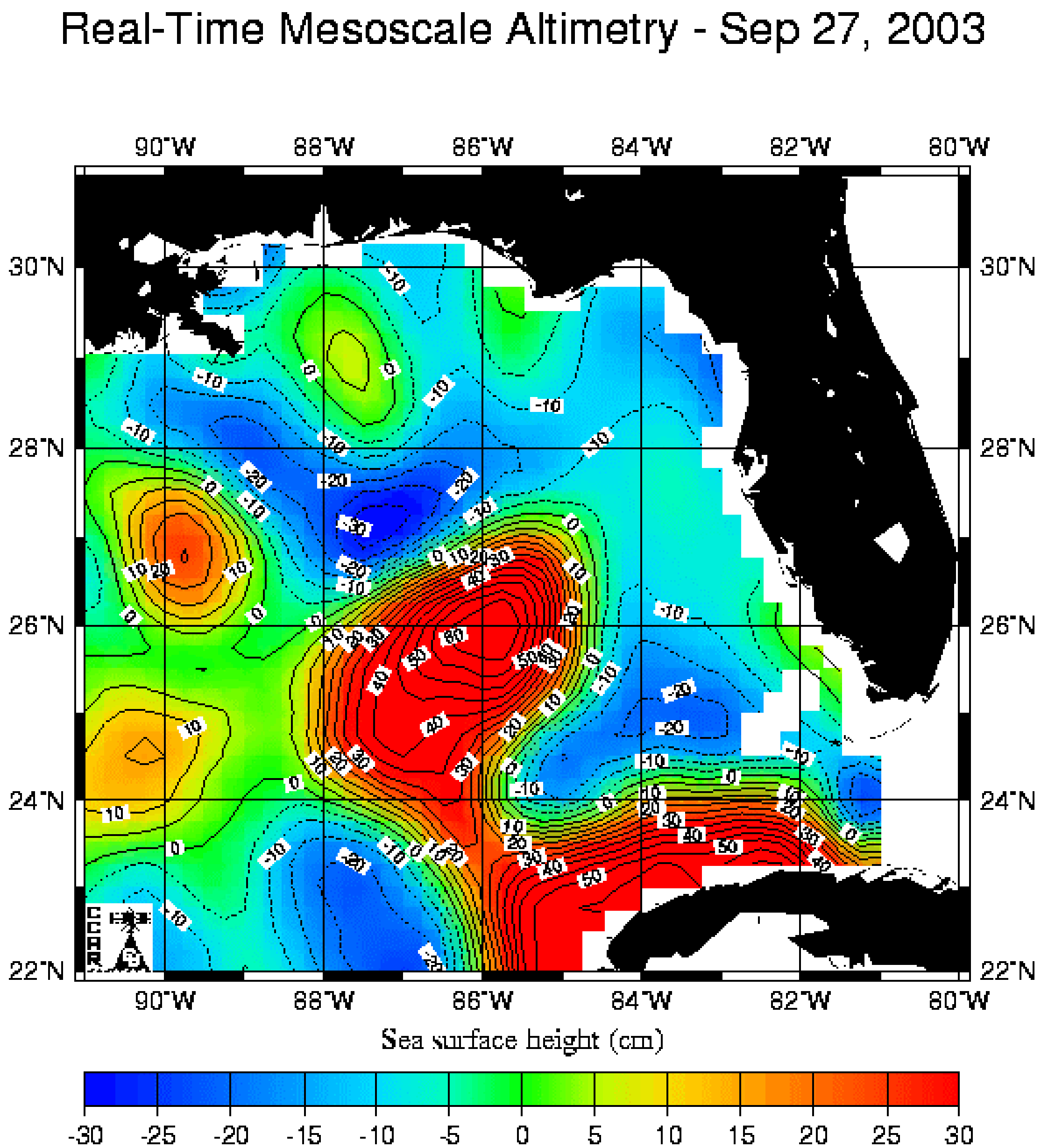


Figure 25. Sea Surface Height (SSH) from satellite altimeters for 27 September 2003 (data courtesy of Dr. Bob Leben of U. Colorado, http://www-ccar.colorado.edu/~realtime/).

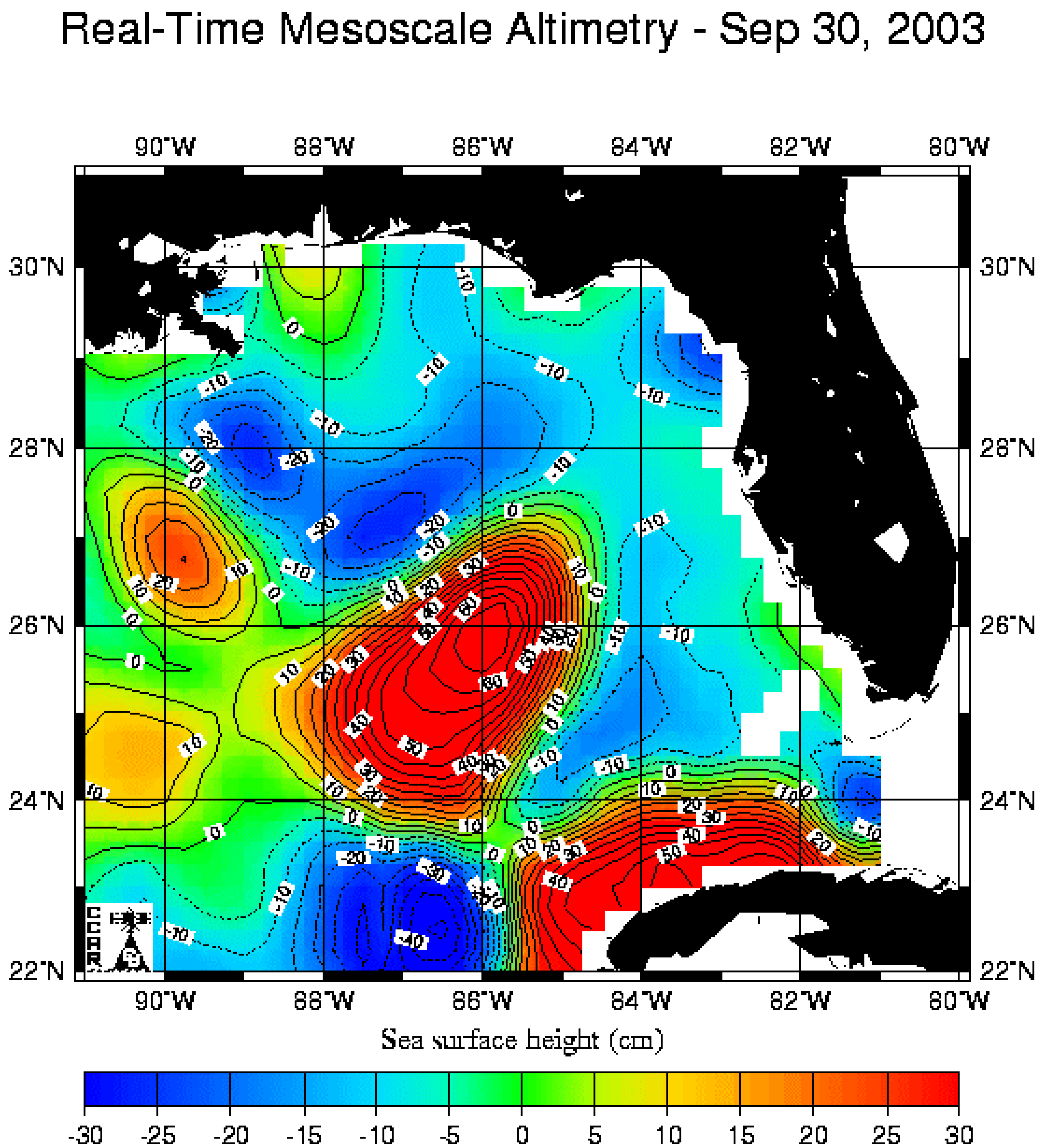


Figure 26. Sea Surface Height (SSH) from satellite altimeters for 30 September 2003 (data courtesy of Dr. Bob Leben of U. Colorado, http://www-ccar.colorado.edu/~realtime/).

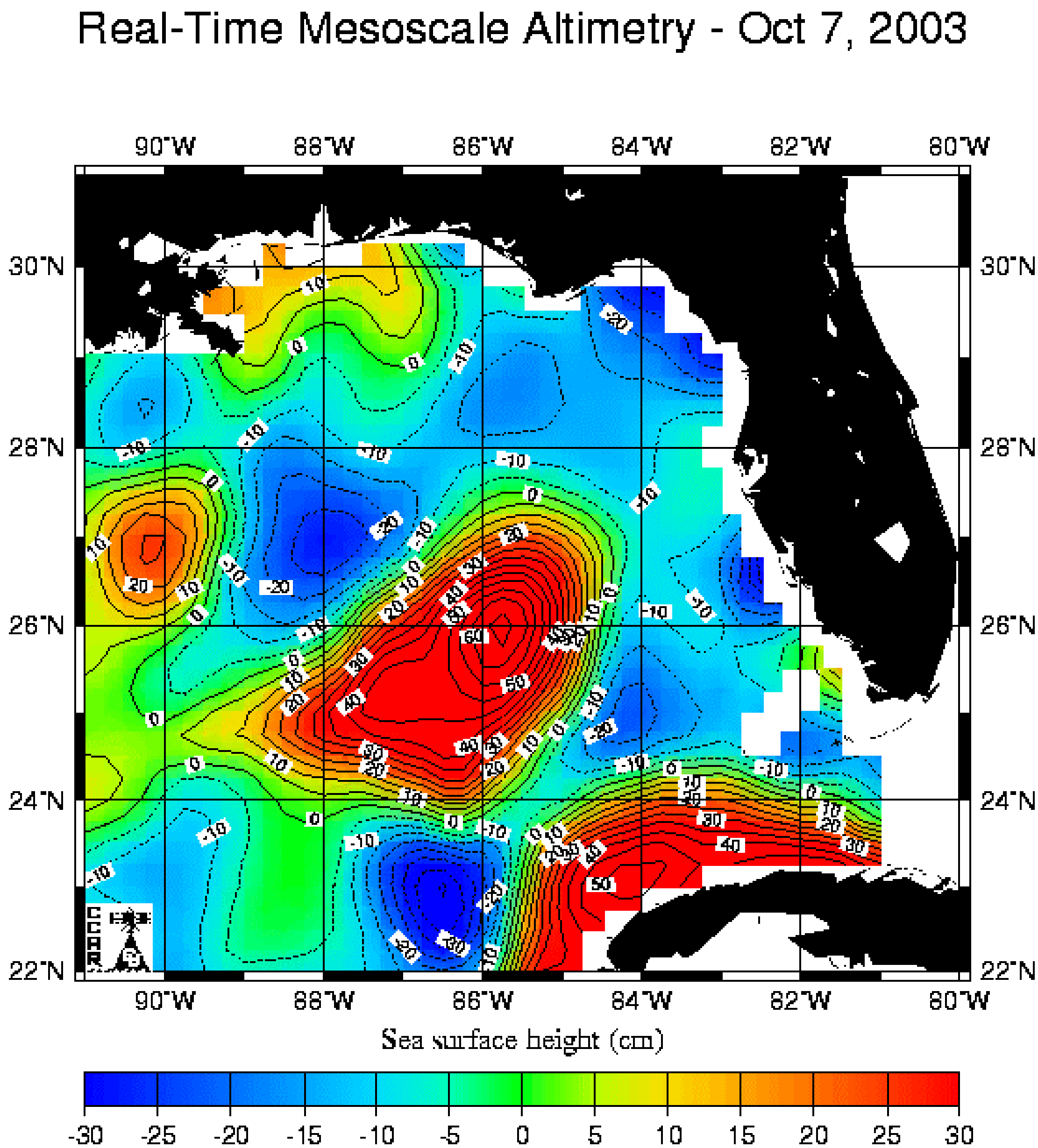


Figure 27. Sea Surface Height (SSH) from satellite altimeters for 7 October 2003 (data courtesy of Dr. Bob Leben of U. Colorado, http://www-ccar.colorado.edu/~realtime/).

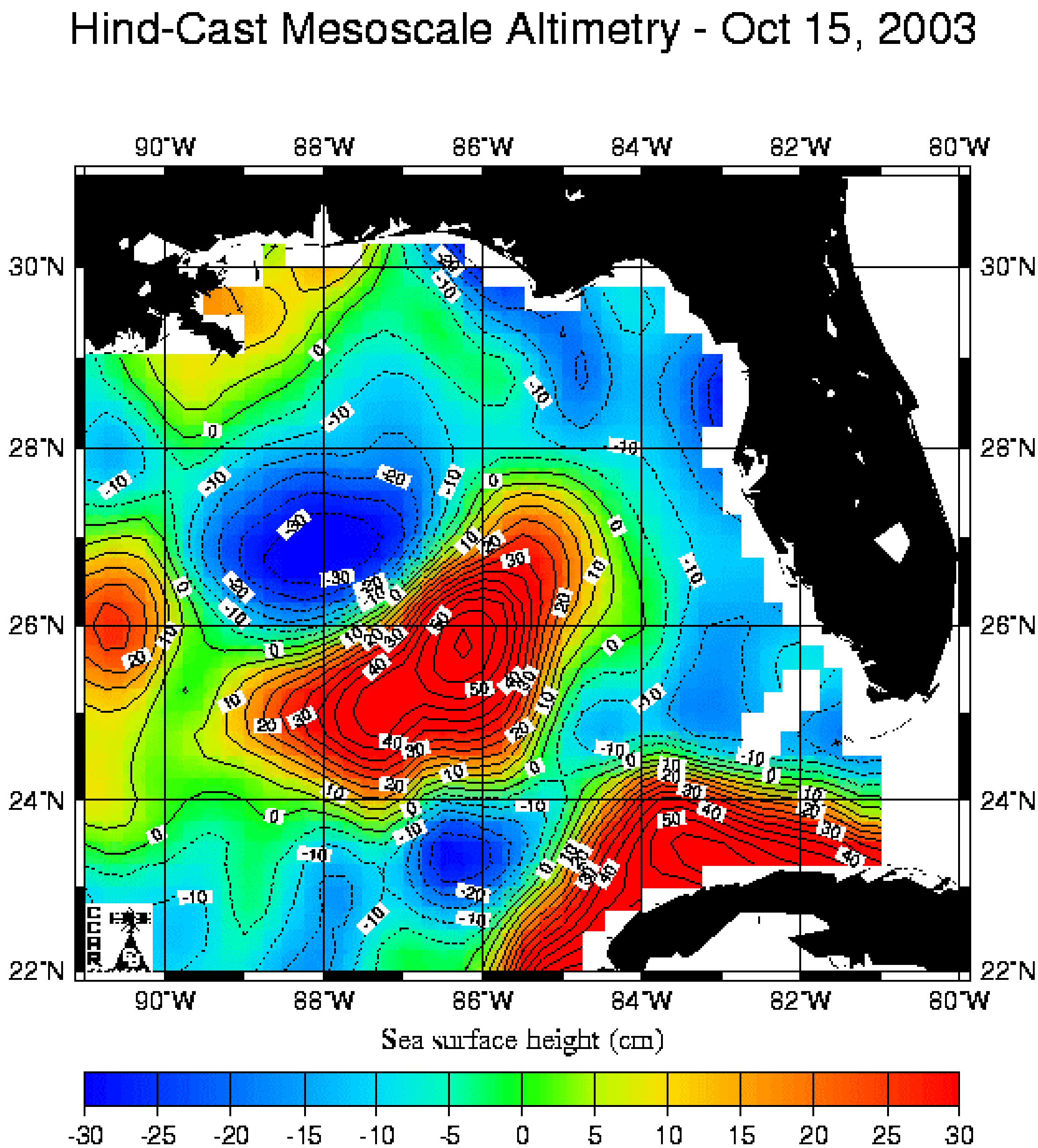


Figure 28. Sea Surface Height (SSH) from satellite altimeters for 15 October 2003 (data courtesy of Dr. Bob Leben of U. Colorado, http://www-ccar.colorado.edu/~realtime/).

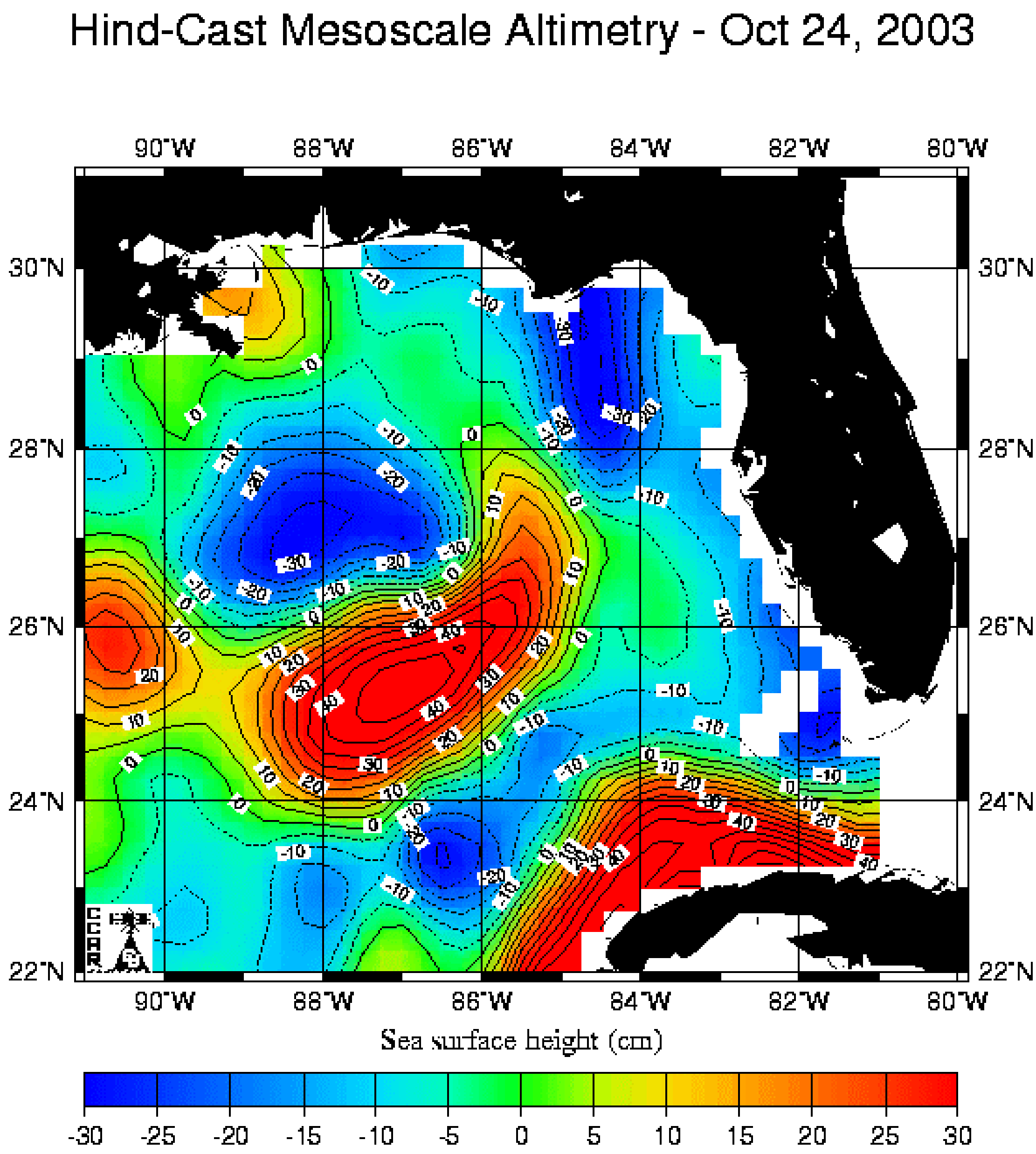


Figure 29. Sea Surface Height (SSH) from satellite altimeters for 24 October 2003 (data courtesy of Dr. Bob Leben of U. Colorado, http://www-ccar.colorado.edu/~realtime/).

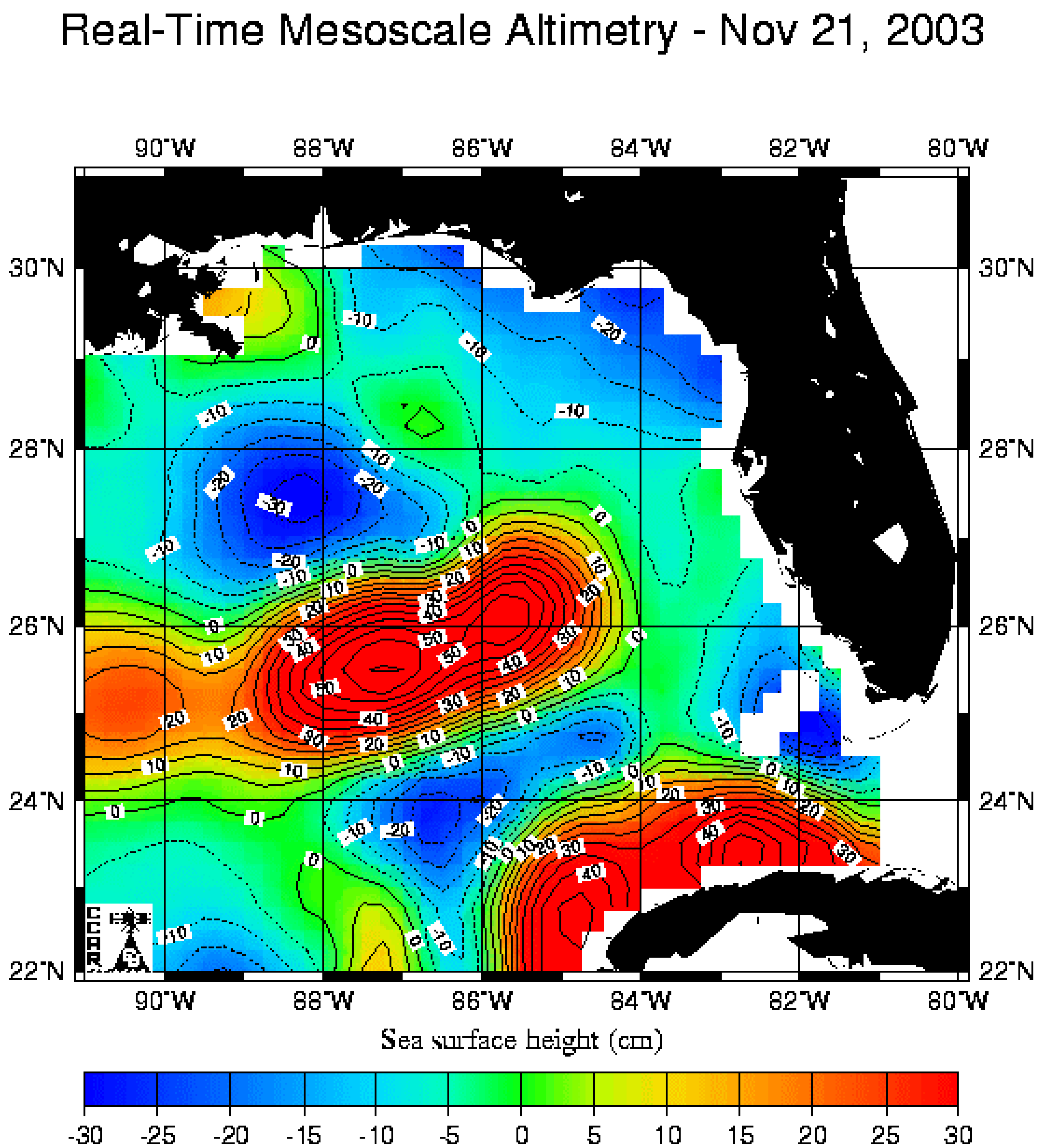


Figure 30. Sea Surface Height (SSH) from satellite altimeters for 21 November 2003 (data courtesy of Dr. Bob Leben of U. Colorado, http://www-ccar.colorado.edu/~realtime/).

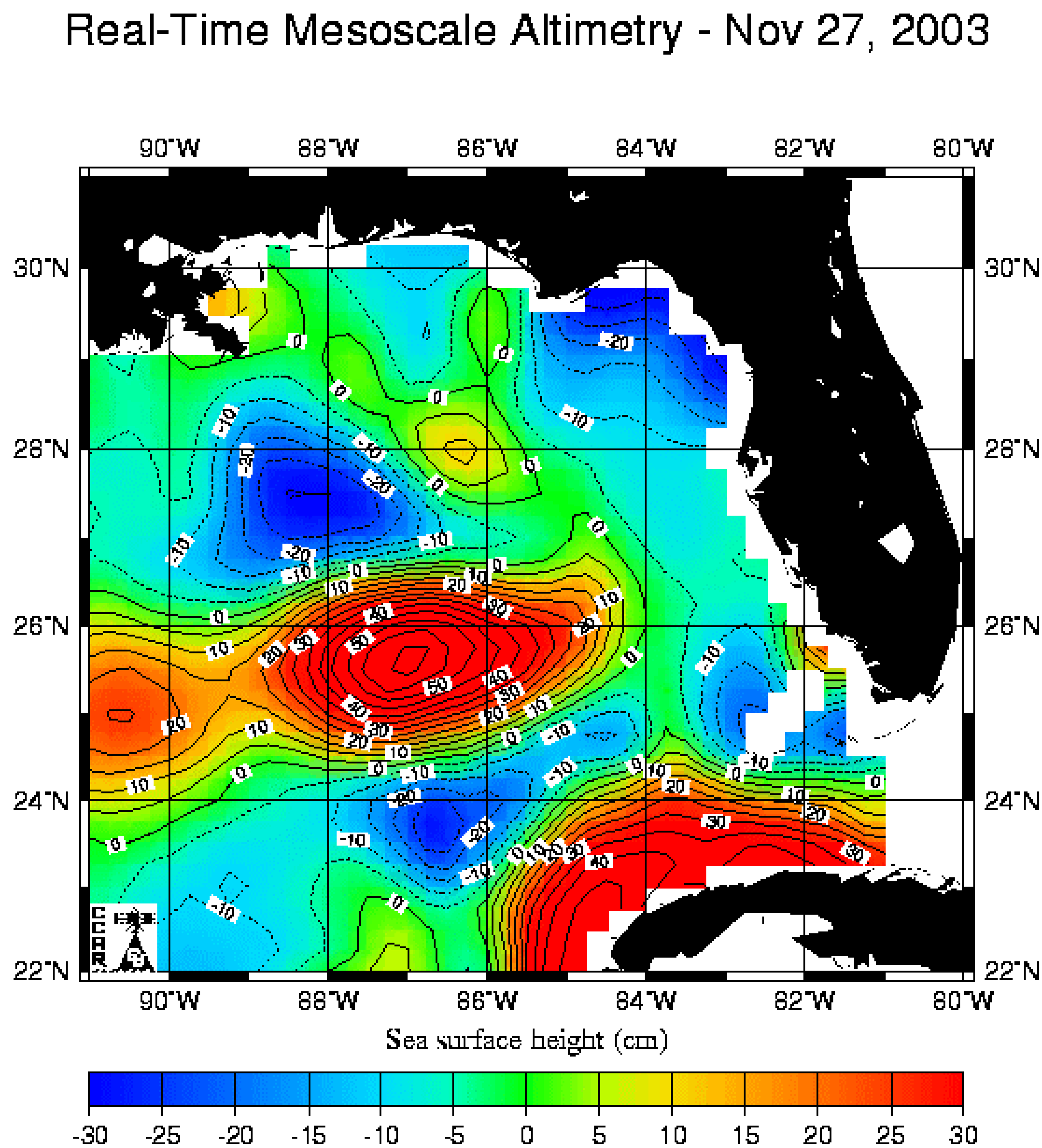


Figure 31. Sea Surface Height (SSH) from satellite altimeters for 27 November 2003 (data courtesy of Dr. Bob Leben of U. Colorado, http://www-ccar.colorado.edu/~realtime/).

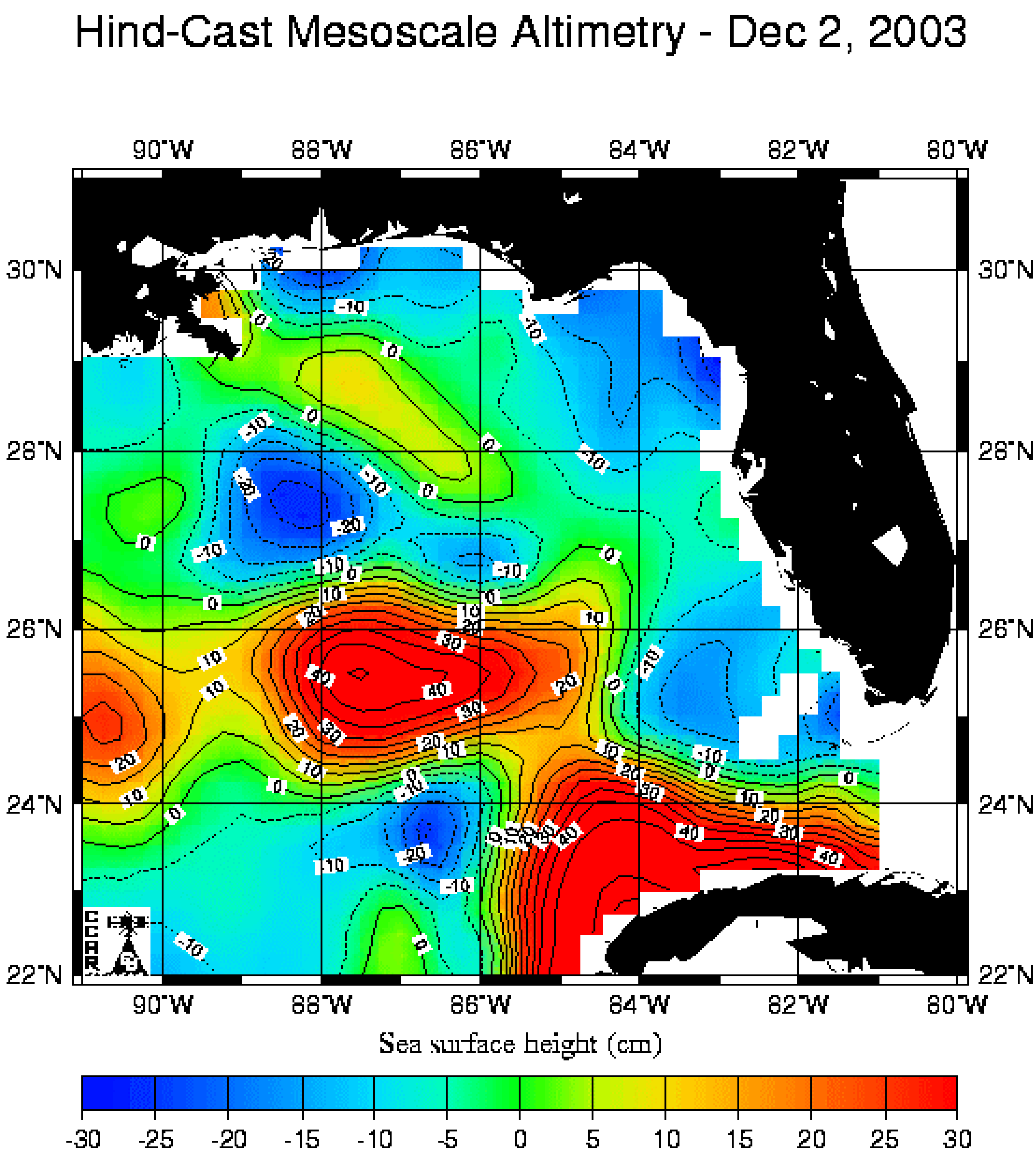


Figure 32. Sea Surface Height (SSH) from satellite altimeters for 2 December 2003 (data courtesy of Dr. Bob Leben of U. Colorado, http://www-ccar.colorado.edu/~realtime/).

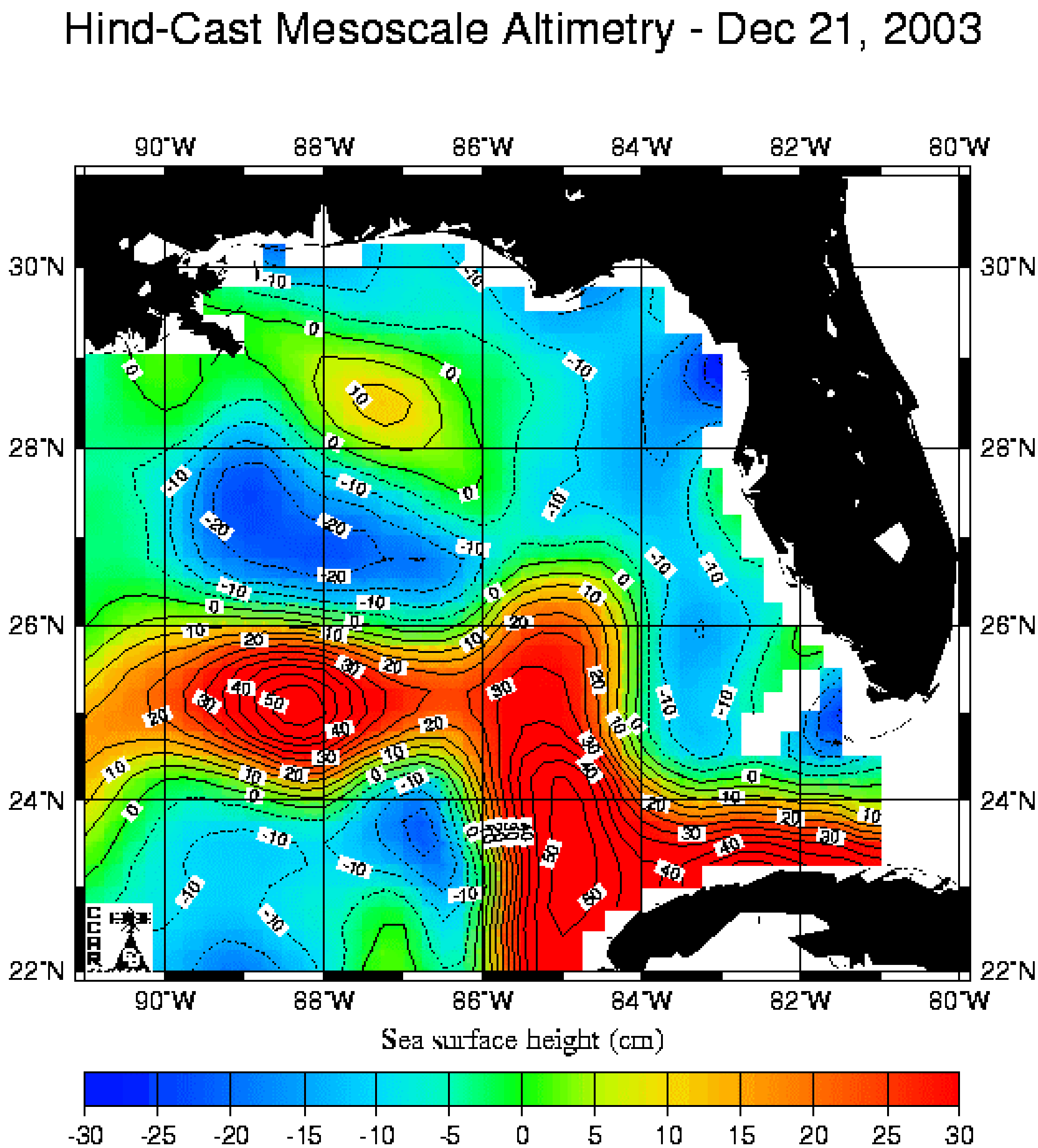


Figure 33. Sea Surface Height (SSH) from satellite altimeters for 21 December (data courtesy of Dr. Bob Leben of U. Colorado, http://www-ccar.colorado.edu/~realtime/).

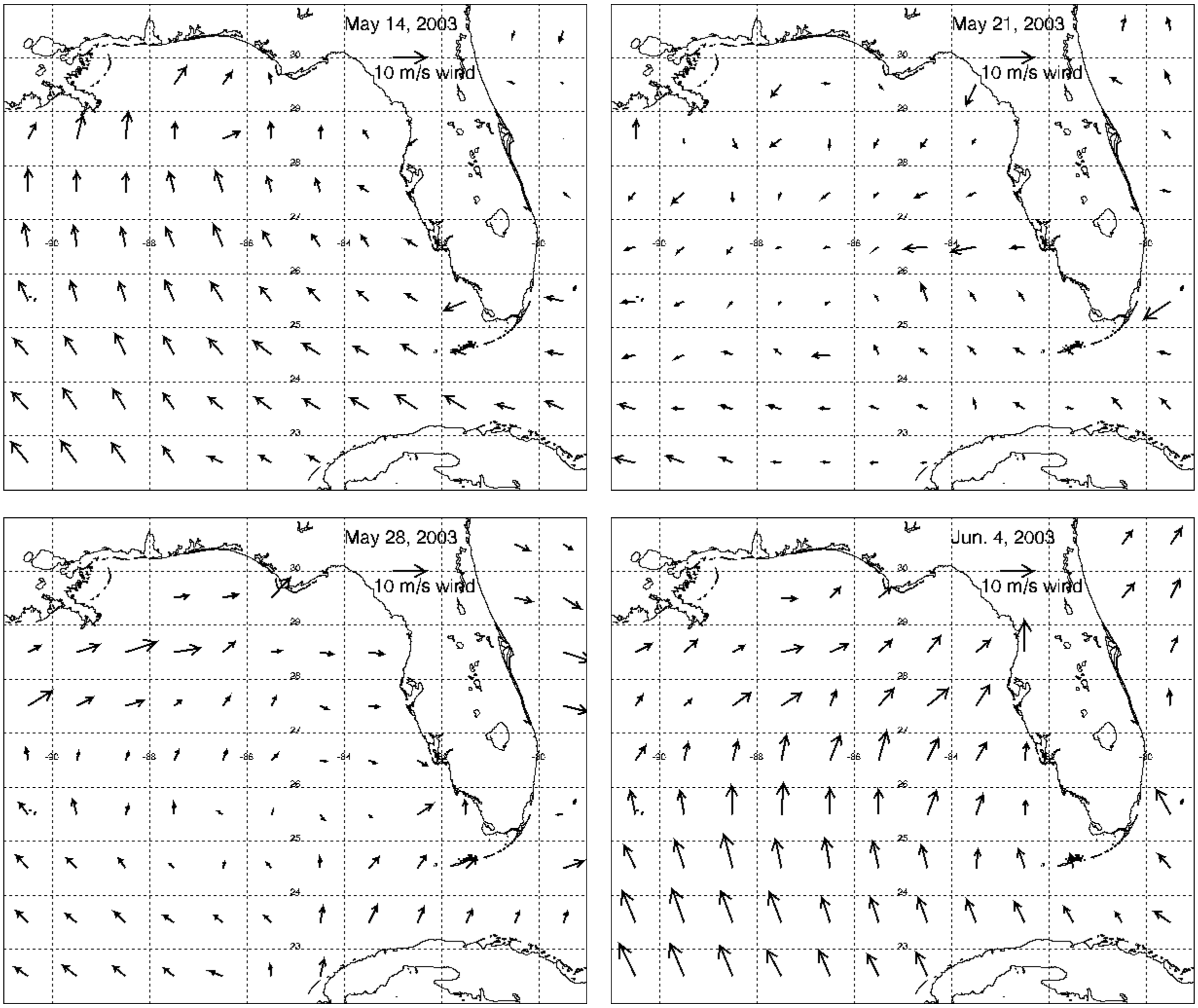


Figure 34. Weekly mean wind from SeaWinds/QuikSCAT radar scatterometer satellite sensor (date shows beginning of the week).

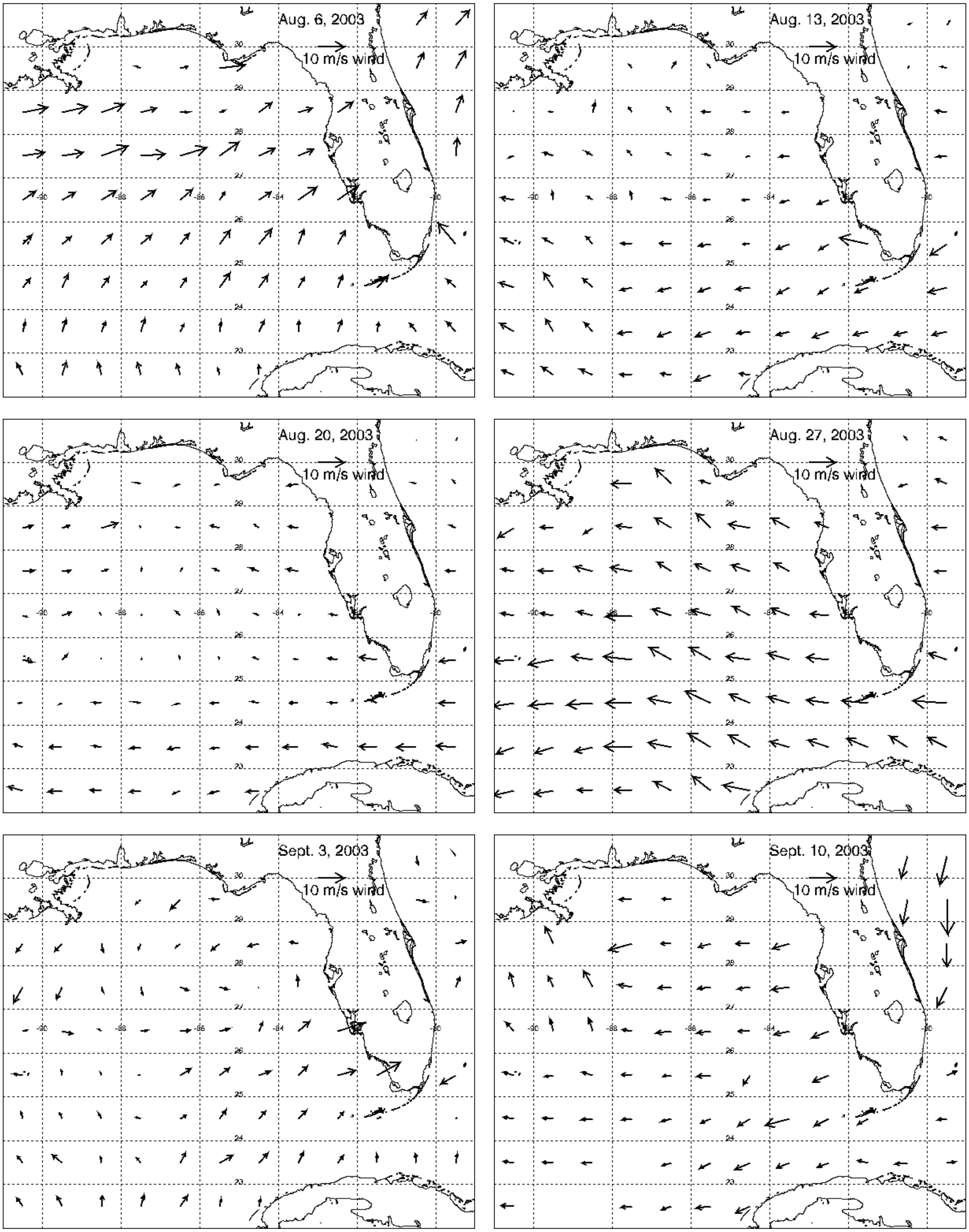


Figure 35. Weekly mean wind from SeaWinds/QuikSCAT (dates show beginning of the week).

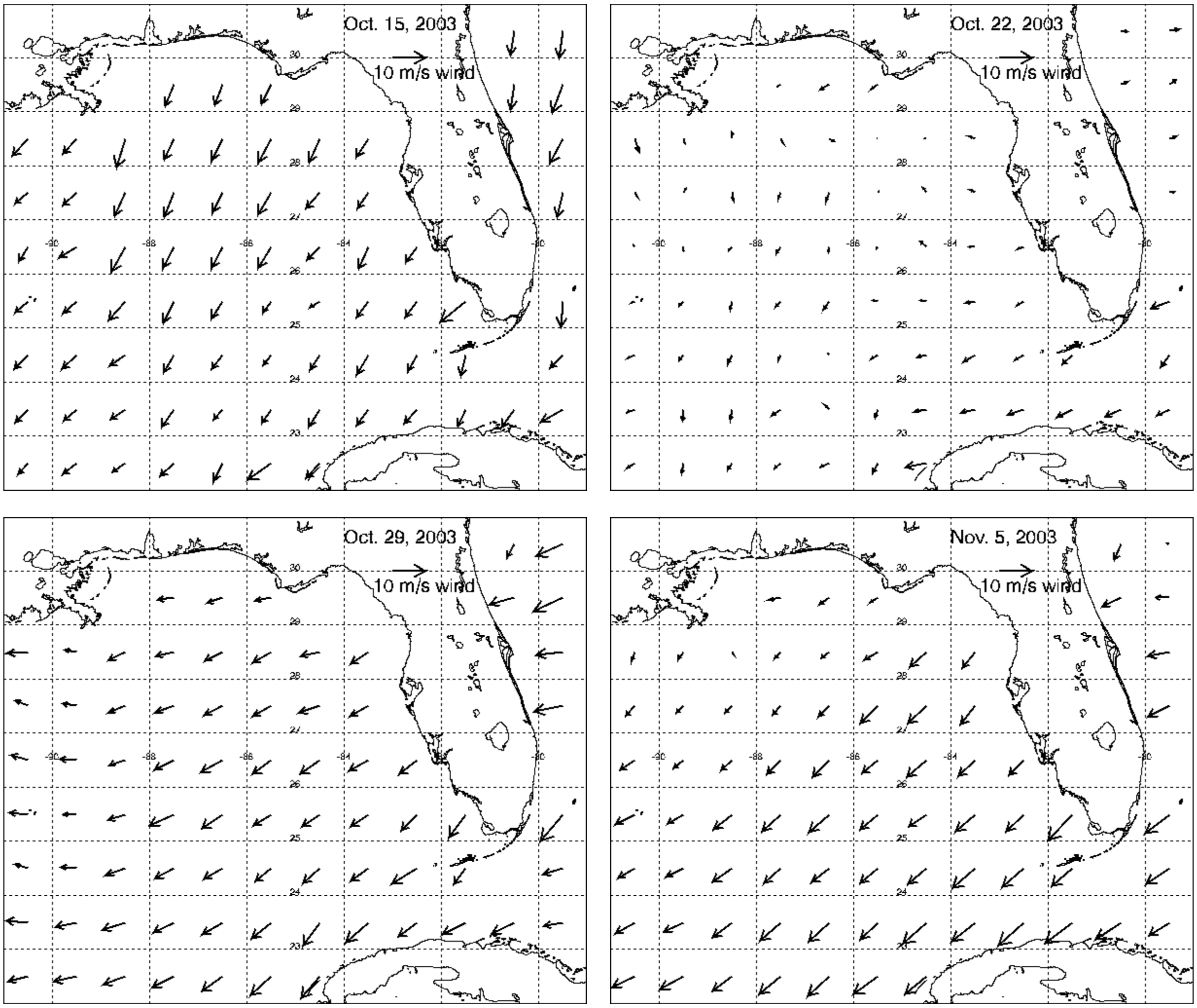


Figure 36. Weekly mean wind from SeaWinds/QuikSCAT (dates show beginning of the week).

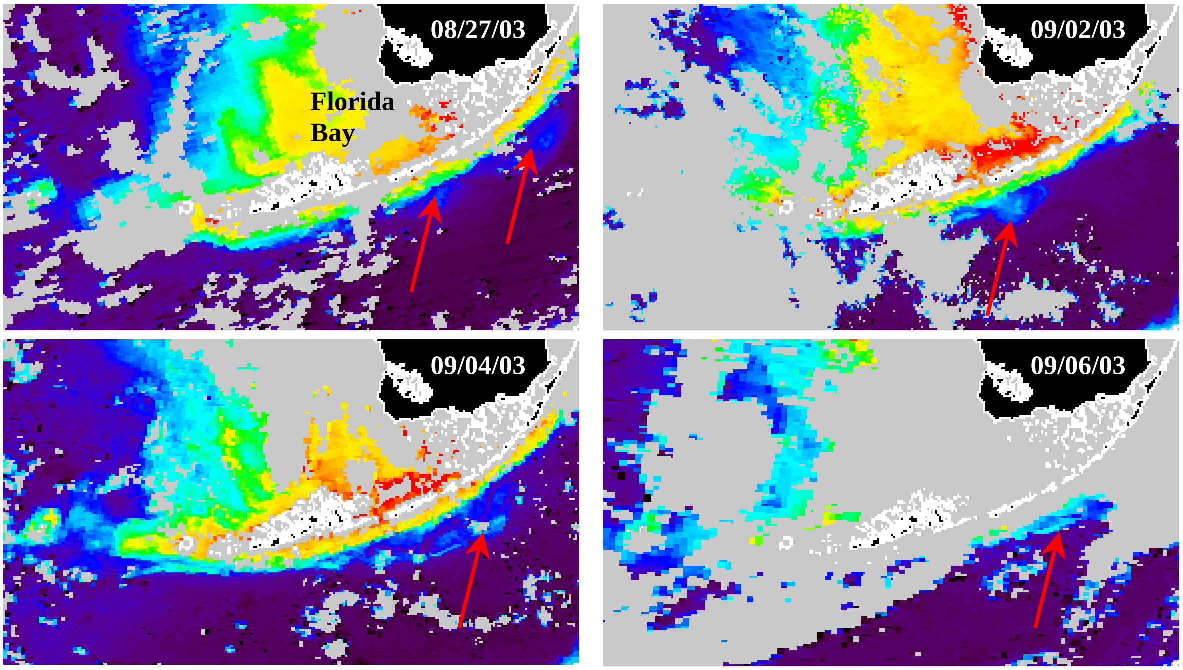
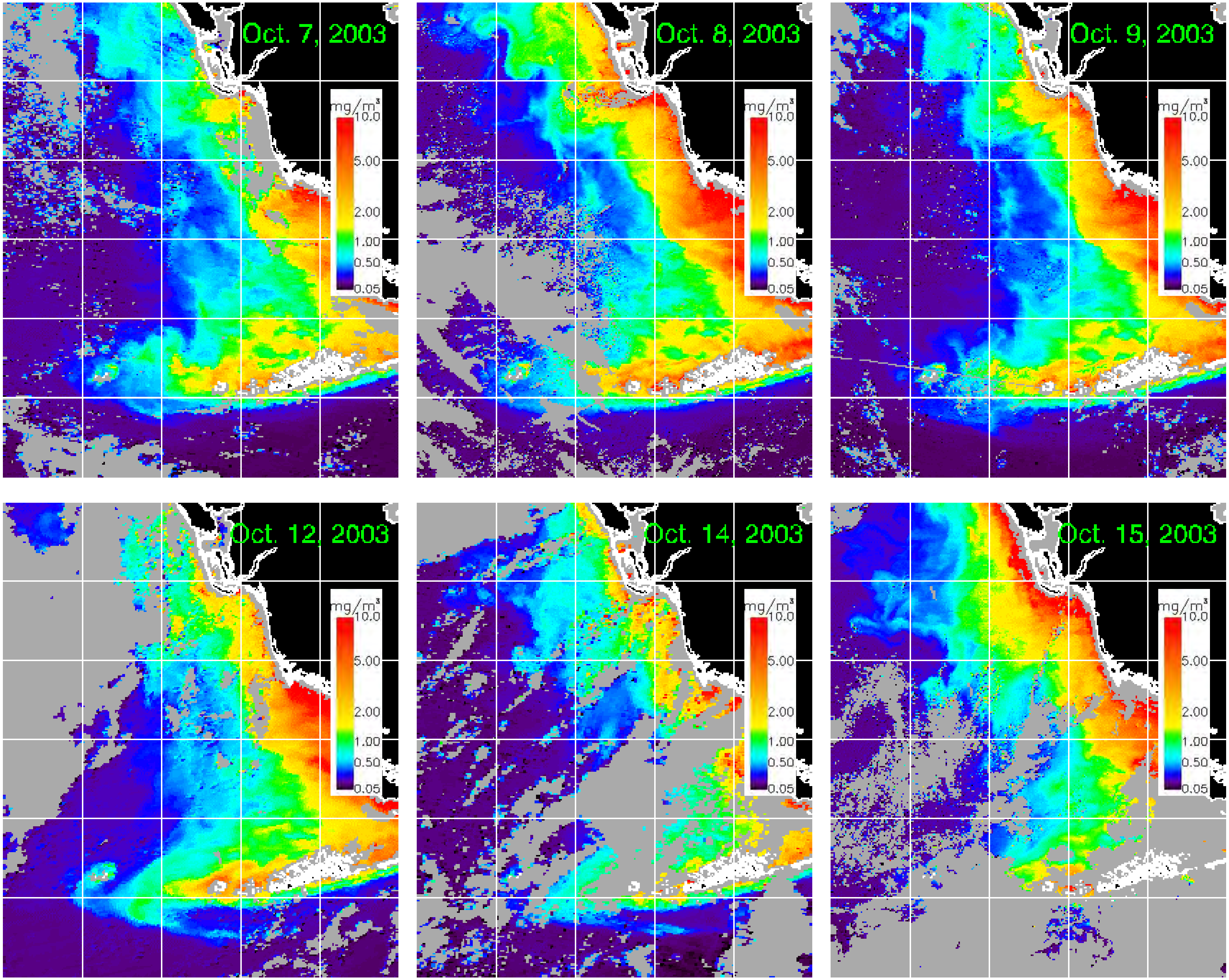
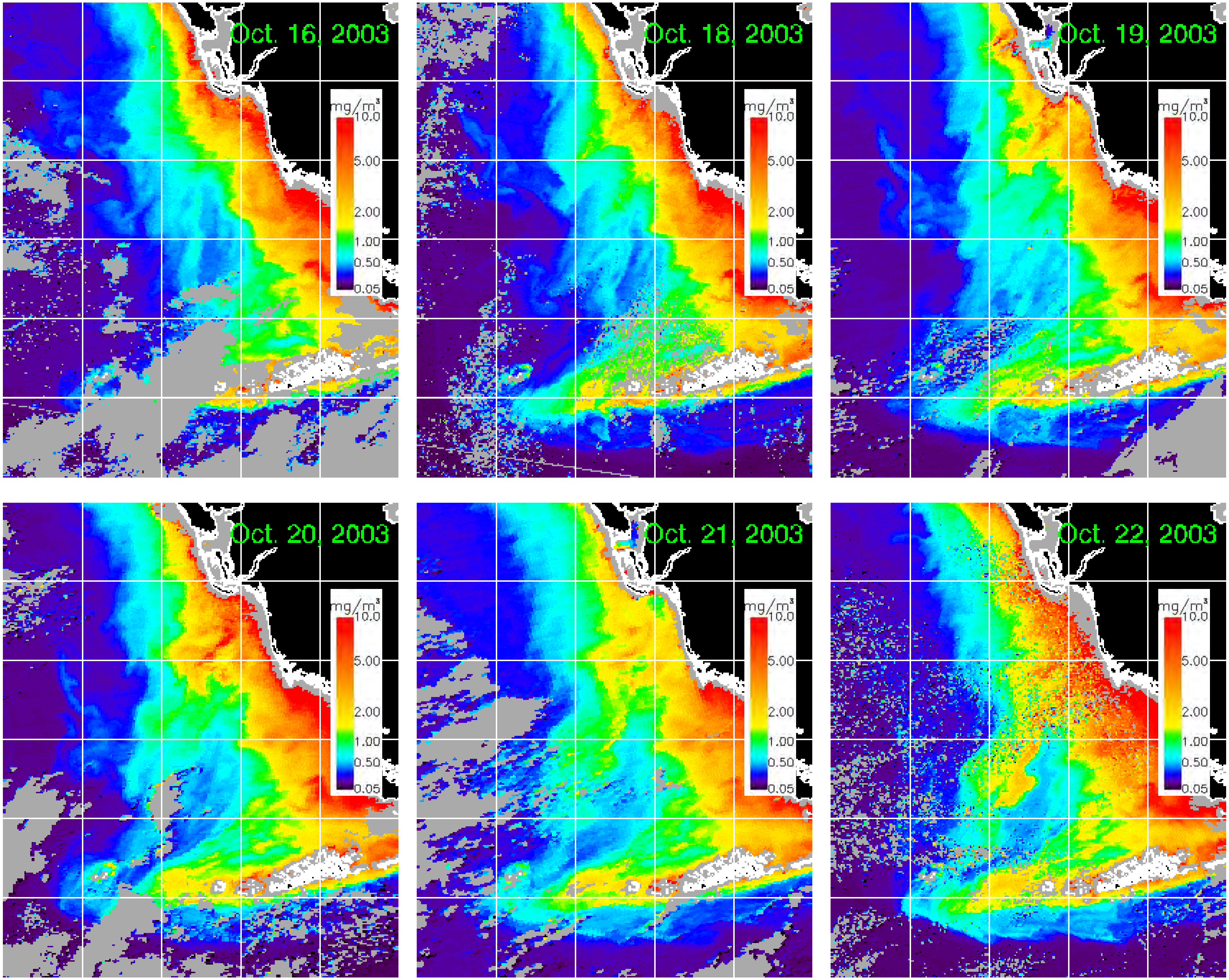


Figure 37. MODIS satellite "chlorophyll" images show color patches (annotated with red arrows) on the ocean side of the Florida Keys.


Oct. 7, 2003
Oct. 8, 2003
Oct. 9, 2003
Oct. 12, 2003
Oct. 14, 2003
Oct. 15, 2003
mg/m³
10.0
5.00
2.00
1.00
0.50
0.05


Oct. 16, 2003
Oct. 18, 2003
Oct. 19, 2003
Oct. 20, 2003
Oct. 21, 2003
Oct. 22, 2003
mg/m^3
10.0
5.00
2.00
1.00
0.50
0.05

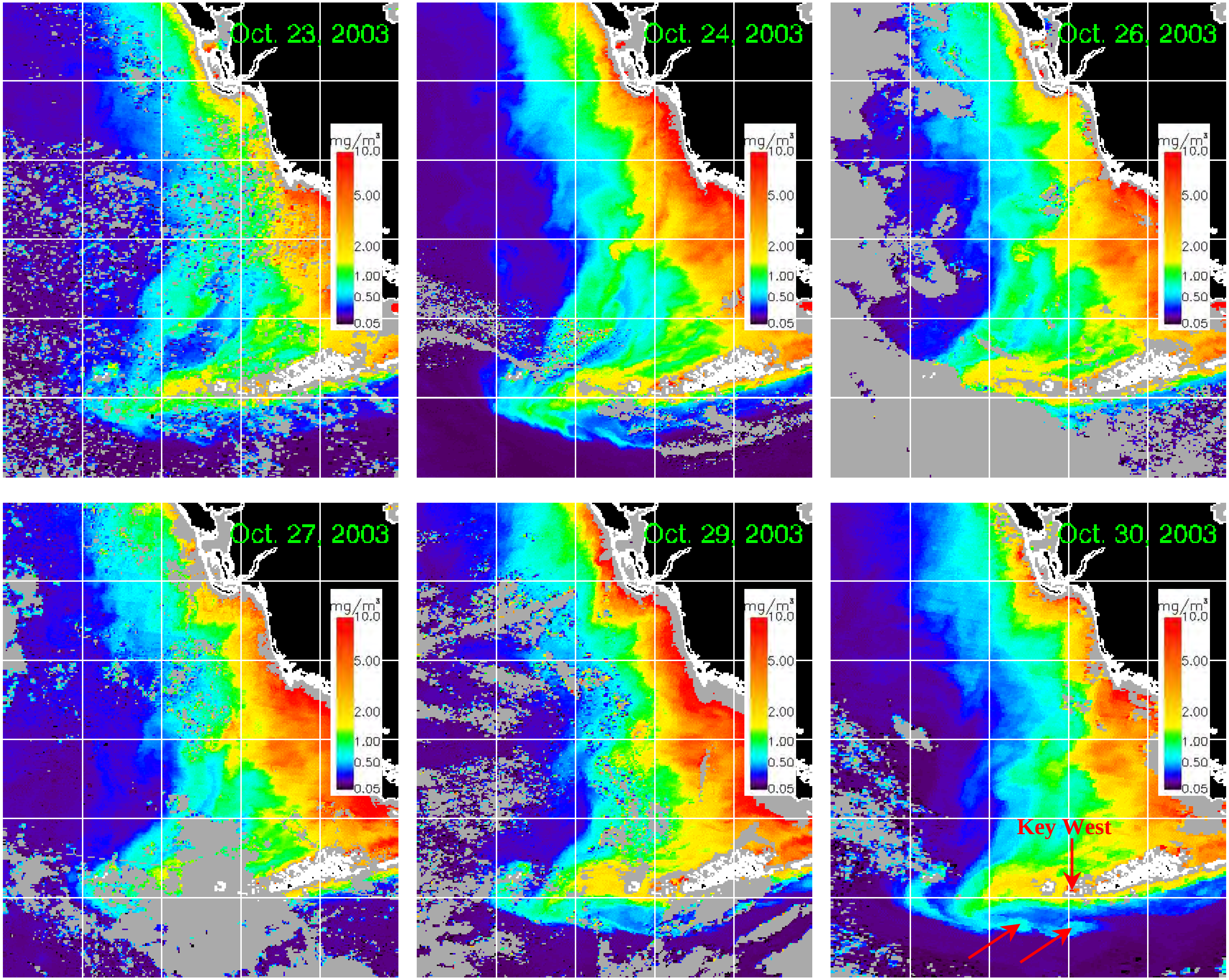

Oct. 23, 2003
Oct. 24, 2003
Oct. 26, 2003
Oct. 27, 2003
Oct. 29, 2003
Oct. 30, 2003
mg/m³
10.0
5.00
2.00
1.00
0.50
0.05
Key West

Figure 38. MODIS satellite "chlorophyll" images showing connection between Charlotte Harbor and the Dry Tortugas. Fishermen view the color patches (annotated on the last panel with red arrows) as "black water." These patches have chlorophyll concentrations of 0.4 to 0.9 mg m^{-3}, and appear dark on satellite true color imagery (note that the images show here are false-color enhanced chlorophyll images). Note that chlorophyll concentrations in the 2002 "black water" were 3 mg m^{-3} or larger.

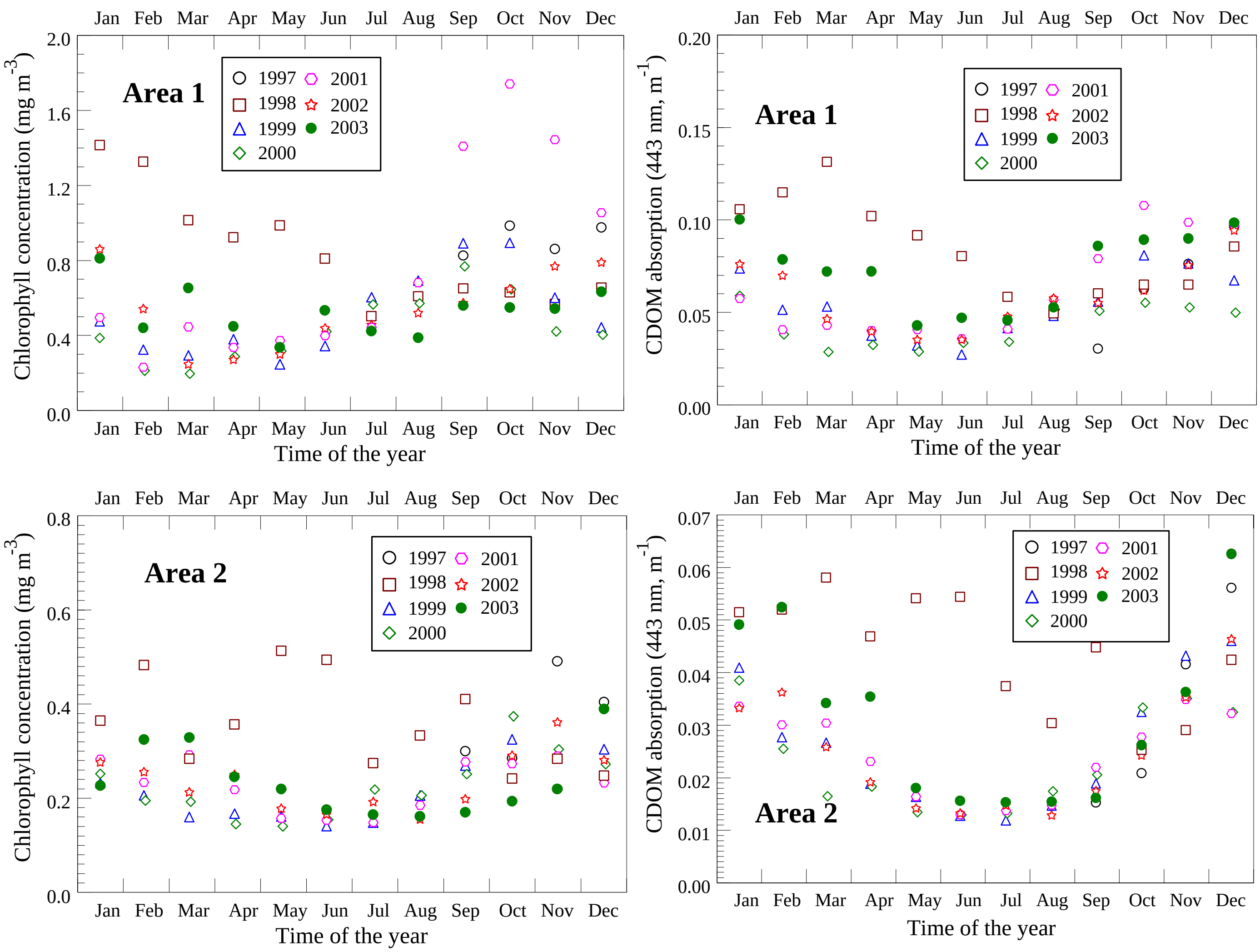


Figure 39. Monthly mean chlorophyll concentrations (in mg m^{-3}) and mean CDOM absorption coefficient (443 nm, m^{-1}) in the surface water, derived from SeaWiFS with a semi-analytical algorithm, for Area 1 and Area 2 outlined in Fig. 11. Note the differences in the y-axis scales.

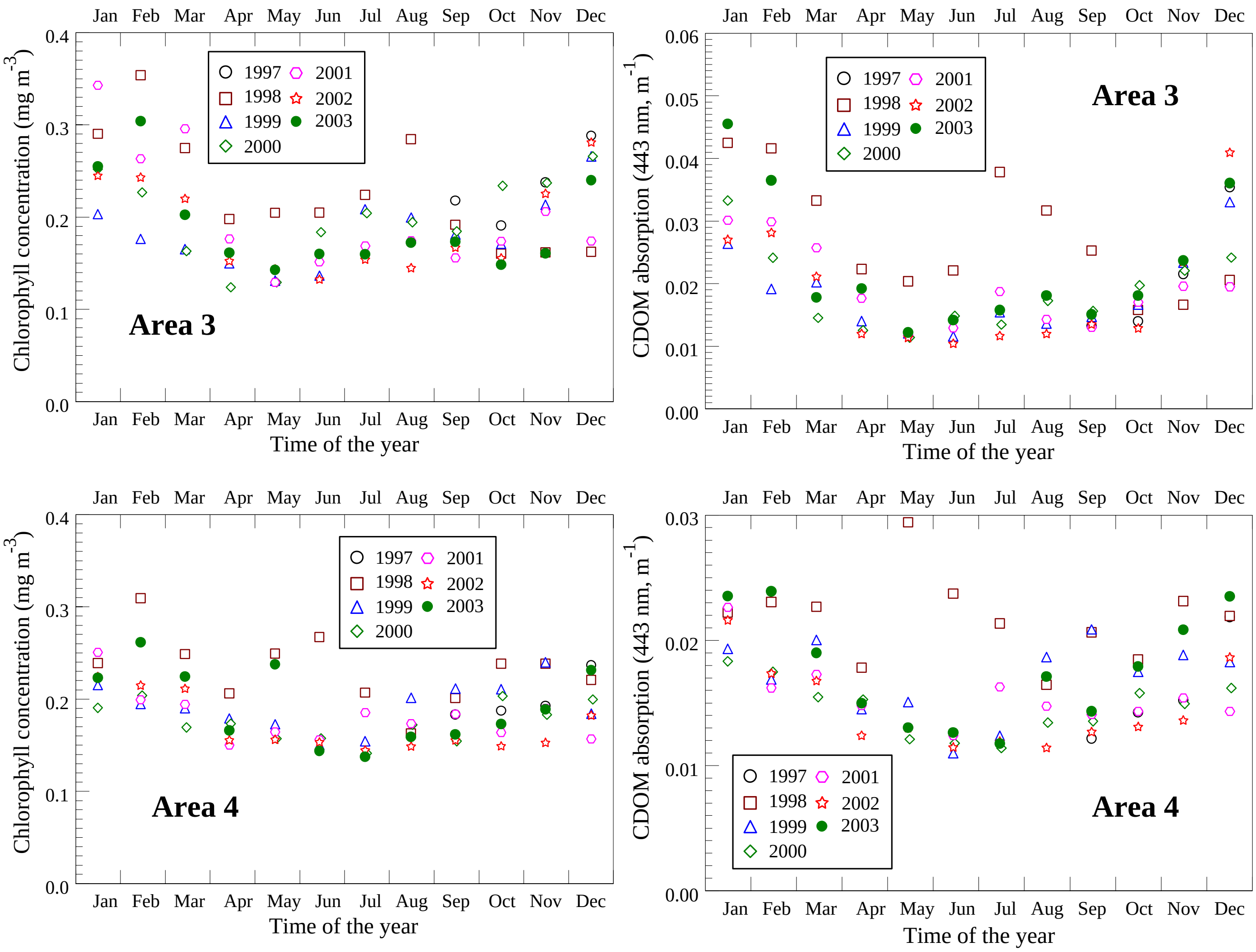


Figure 40. Monthly mean chlorophyll concentrations (in mg m^{-3}) and mean CDOM absorption coefficient (443 nm, m^{-1}) in the surface water, derived from SeaWiFS with a semi-analytical algorithm, for Area 3 and Area 4 outlined in Fig. 11. Note the differences in the y-axis scales.

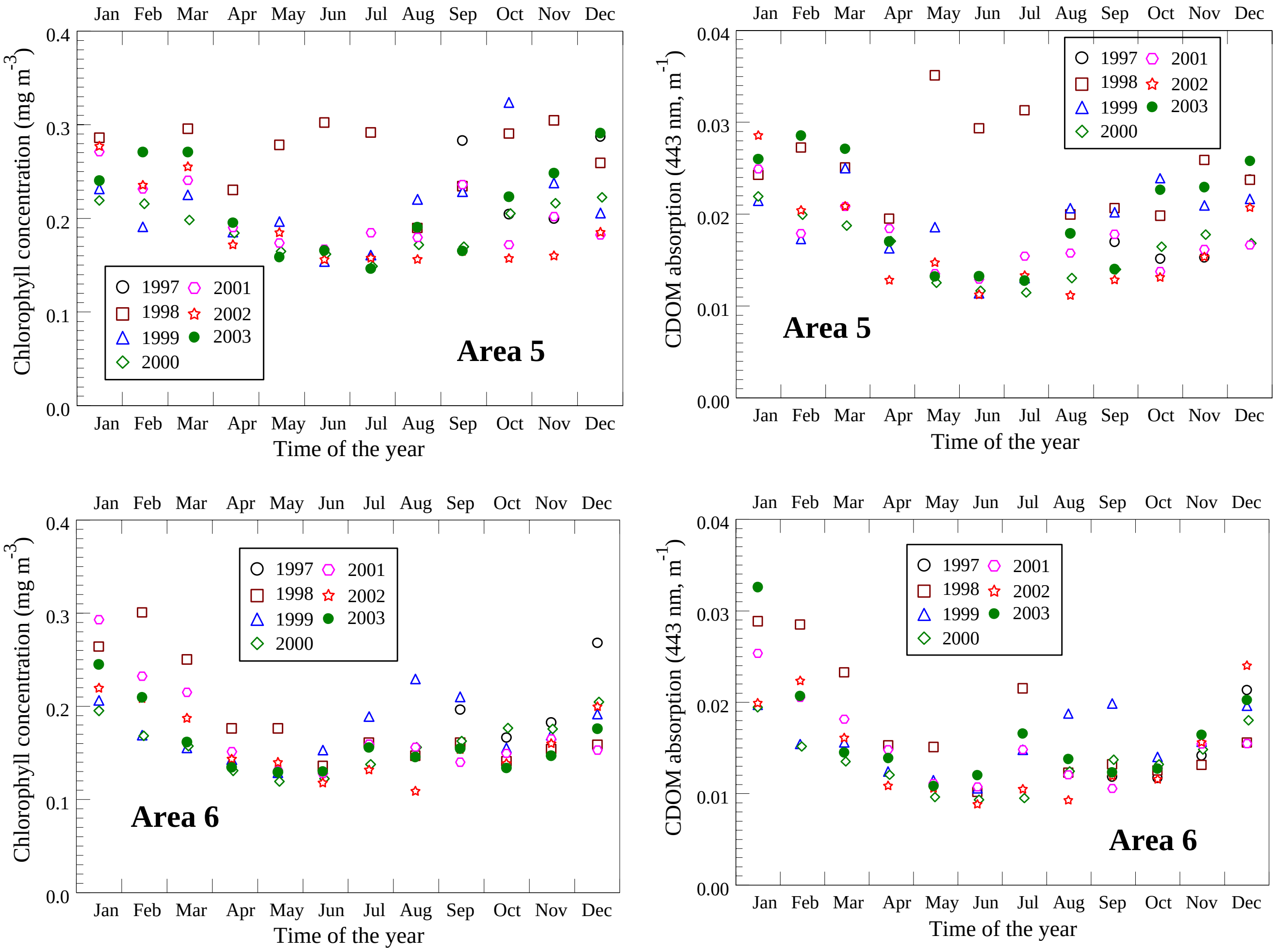


Figure 41. Monthly mean chlorophyll concentrations (in mg m^{-3}) and mean CDOM absorption coefficient (443 nm, m^{-1}) in the surface water, derived from SeaWiFS with a semi-analytical algorithm, for Area 5 and Area 6 outlined in Fig. 11.

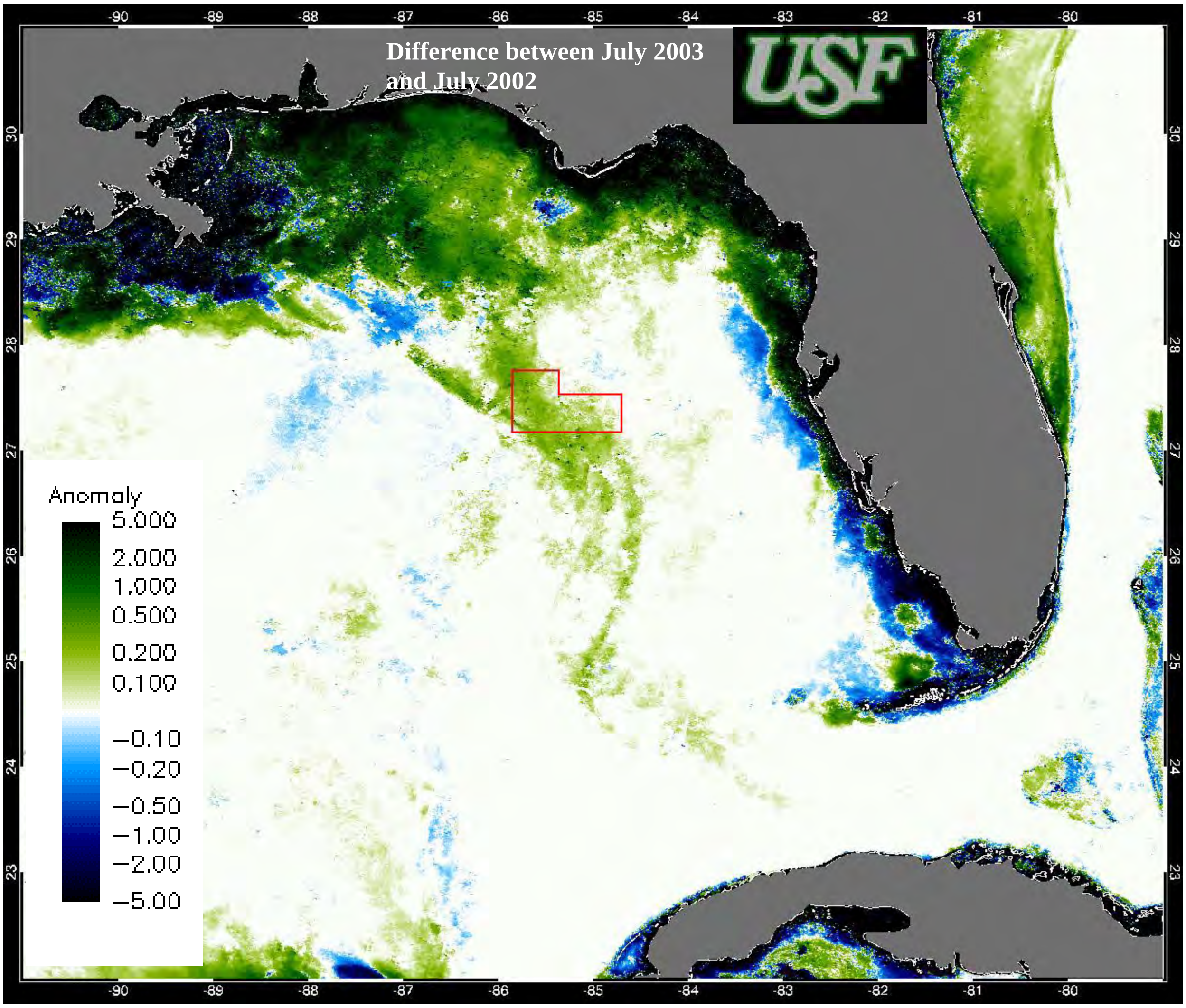


Figure 42. Difference between the mean surface chlorophyll concentration of July 2003 and July 2002 from SeaWiFS data (mg m^{-3}, standard NASA algorithm). Green means higher concentrations this year than the same period of last year. White color represents no change (differences smaller than ±0.05 mg m^{-3}) or no data for either of the two periods. The discharge area is outlined as a red box. Blue shows areas that had a lower concentration this year relative to last year for this period.

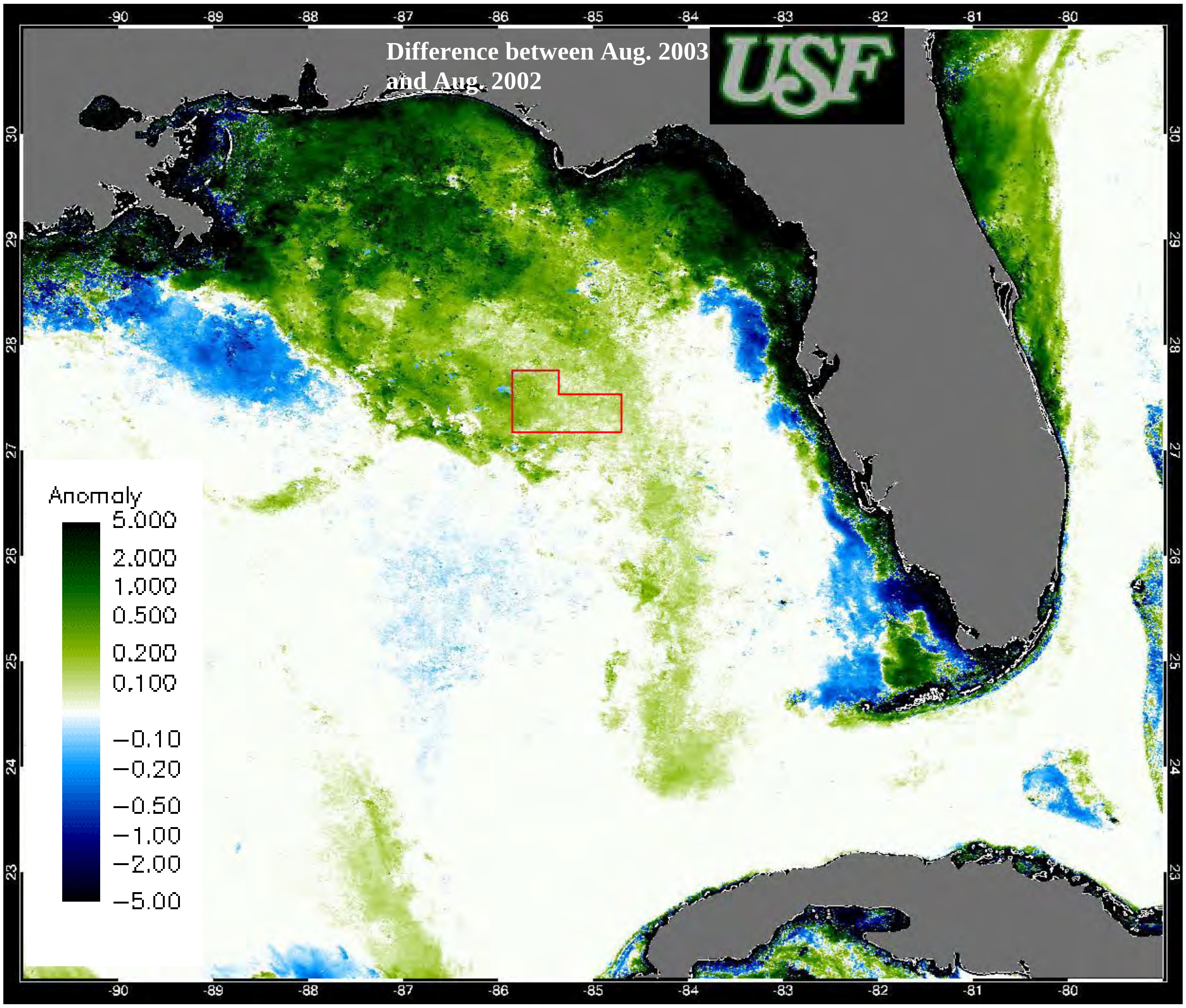


Figure 43. Difference between the mean surface chlorophyll concentration of August 2003 and August 2002 from SeaWiFS data (mg m^{-3}, standard NASA algorithm). Green means higher concentrations this year than the same period of last year. White color represents no change (differences smaller than ±0.05 mg m^{-3}) or no data for either of the two periods. The discharge area is outlined as a red box. Blue shows areas that had a lower concentration this year relative to last year for this period.

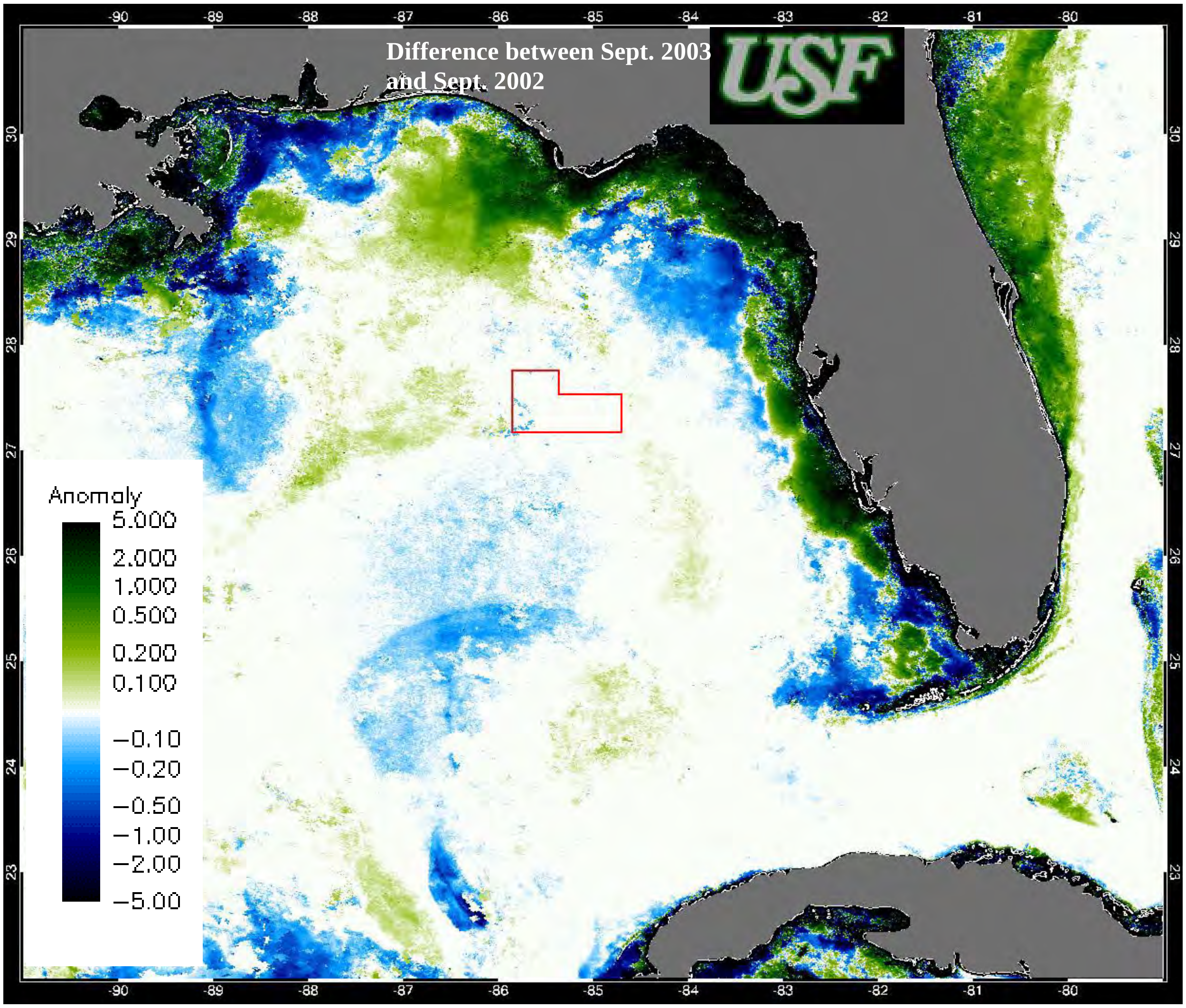


Figure 44. Difference between the mean surface chlorophyll concentration of September 2003 and September 2002 from SeaWiFS data (mg m^{-3}, standard NASA algorithm). Green means higher concentrations this year than the same period of last year. White color represents no change (differences smaller than ±0.05 mg m^{-3}) or no data for either of the two periods. The discharge area is outlined as a red box. Blue shows areas that had a lower concentration this year relative to last year for this period.

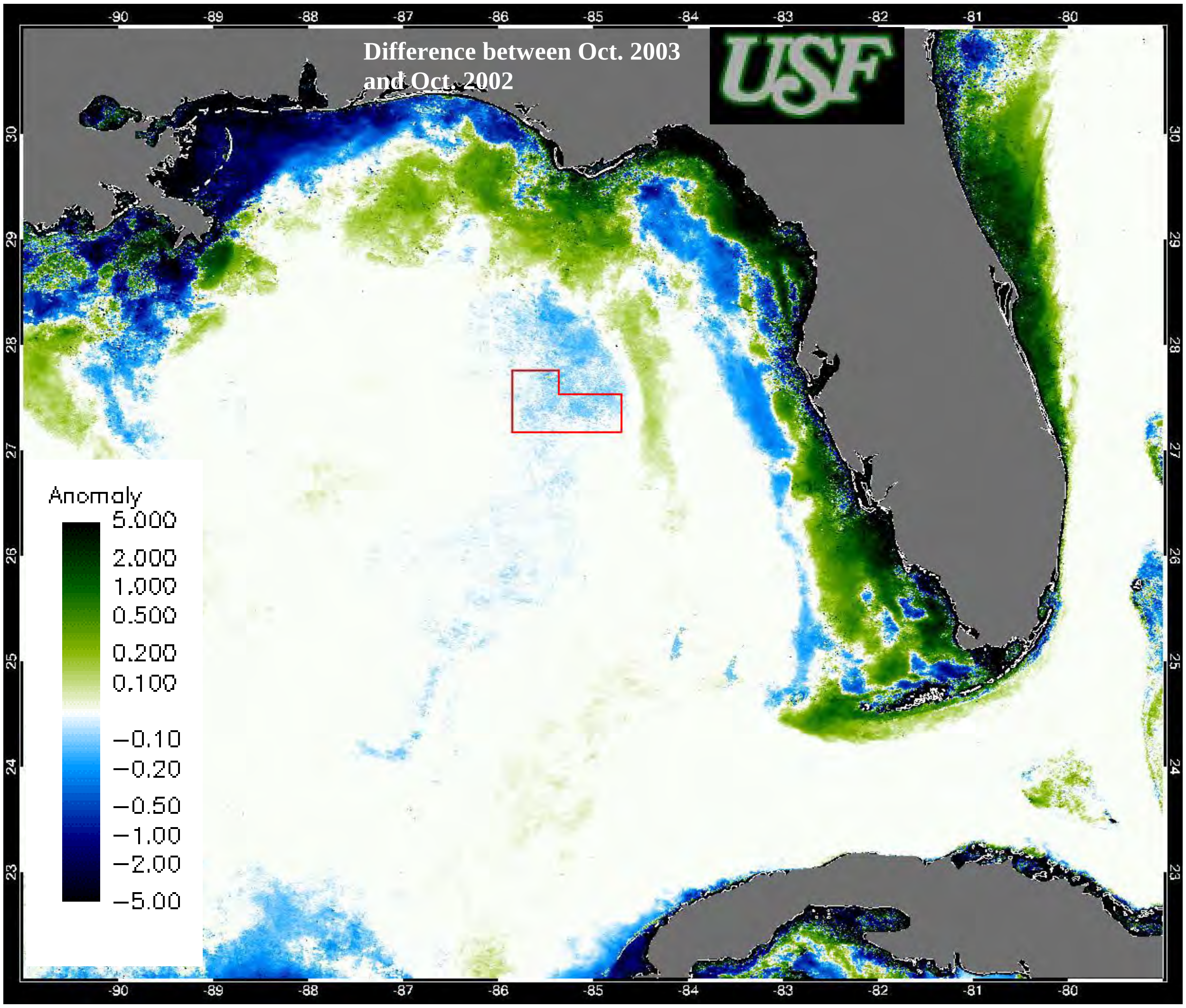


Figure 45. Difference between the mean surface chlorophyll concentration of October 2003 and October 2002 from SeaWiFS data (mg m^{-3}, standard NASA algorithm). Green means higher concentrations this year than the same period of last year. White color represents no change (differences smaller than ±0.05 mg m^{-3}) or no data for either of the two periods. The discharge area is outlined as a red box. Blue shows areas that had a lower concentration this year relative to last year for this period.

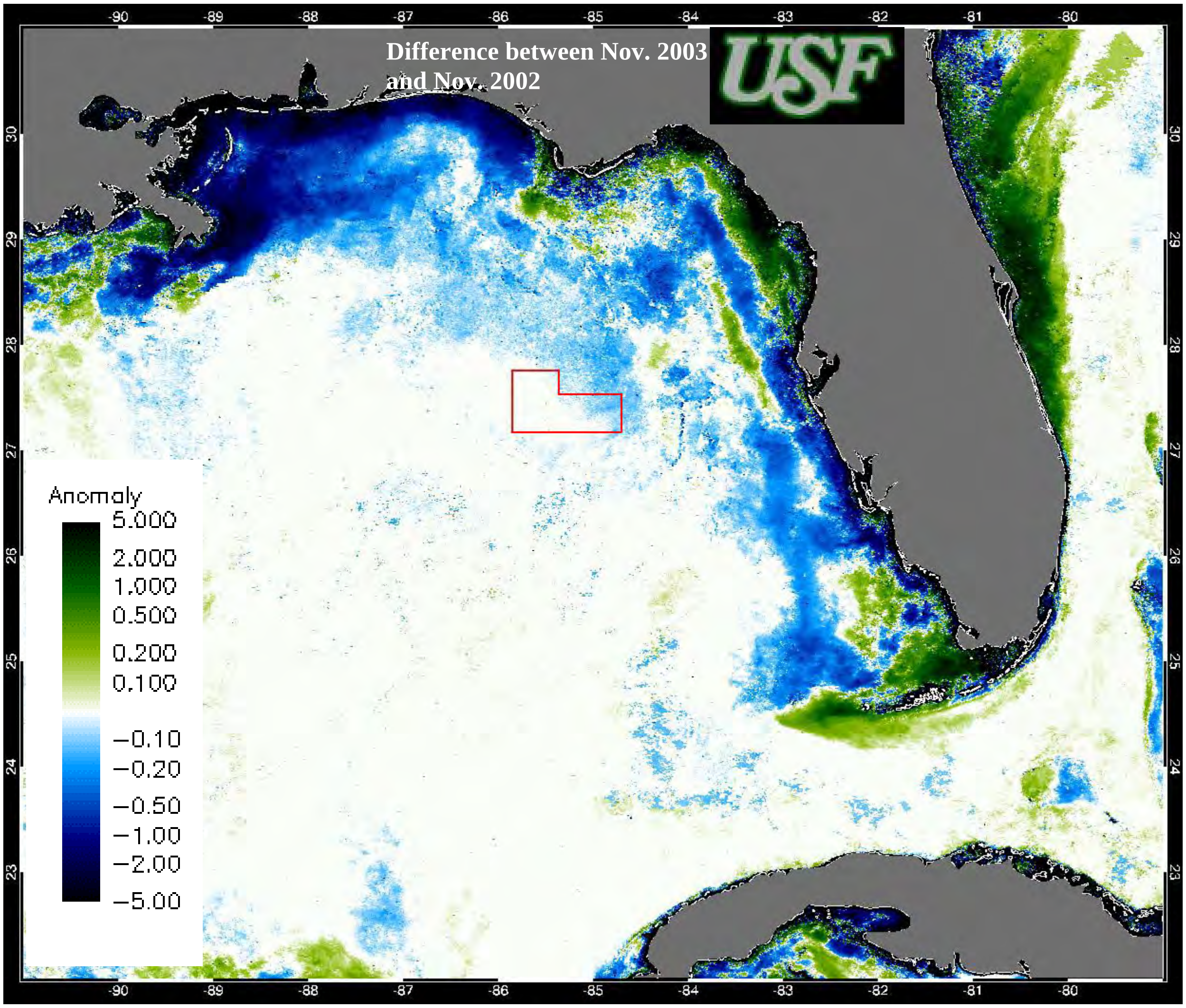


Figure 46. Difference between the mean surface chlorophyll concentration of November 2003 and November 2002 from SeaWiFS data (mg m^{-3}, standard NASA algorithm). Green means higher concentrations this year than the same period of last year. White color represents no change (differences smaller than ±0.05 mg m^{-3}) or no data for either of the two periods. The discharge area is outlined as a red box. Blue shows areas that had a lower concentration this year relative to last year for this period.

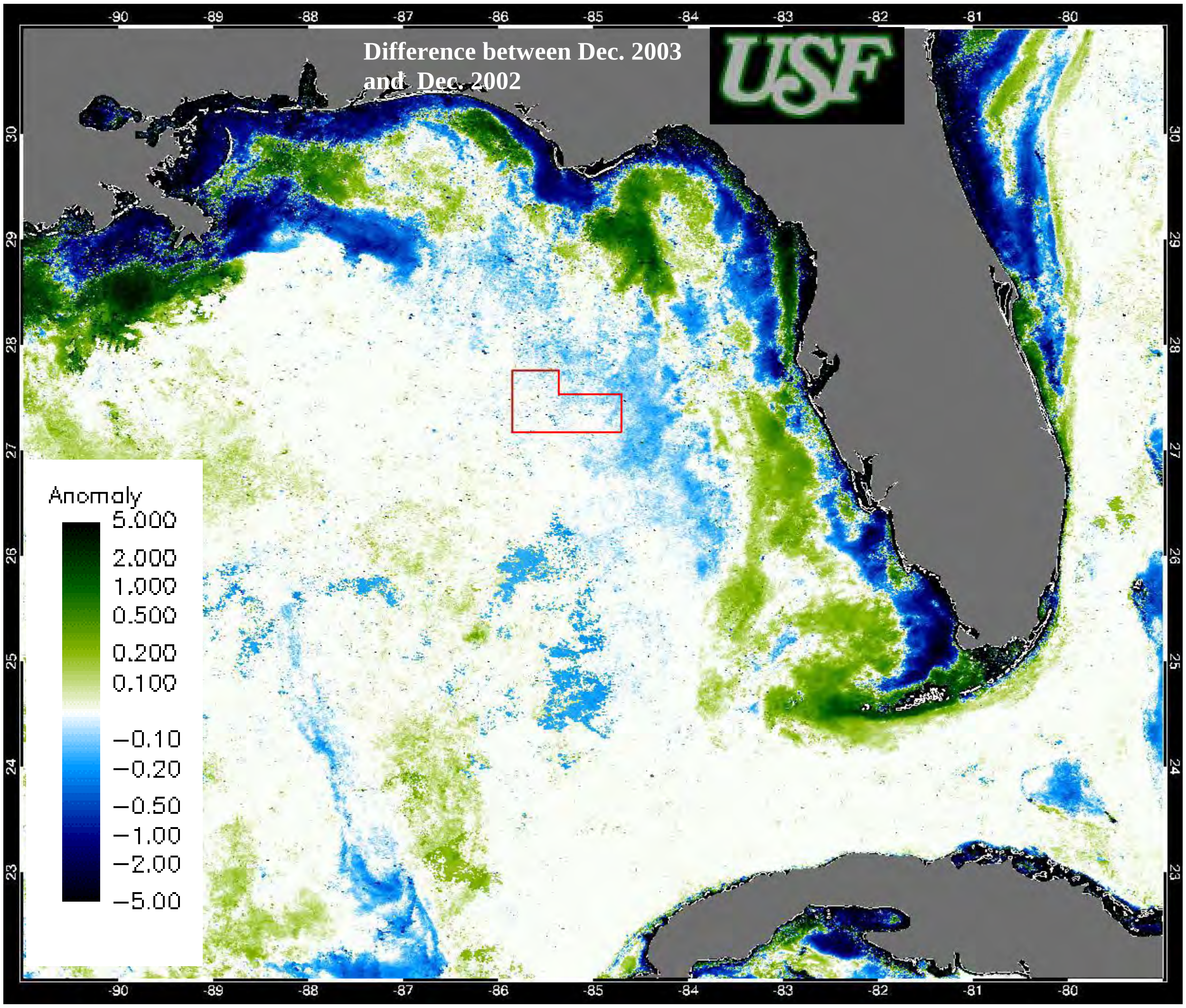


Figure 47. Difference between the mean surface chlorophyll concentration of December 2003 and December 2002 from SeaWiFS data (mg m^{-3}, standard NASA algorithm). Green means higher concentrations this year than the same period of last year. White color represents no change (differences smaller than ±0.05 mg m^{-3}) or no data for either of the two periods. The discharge area is outlined as a red box. Blue shows areas that had a lower concentration this year relative to last year for this period.

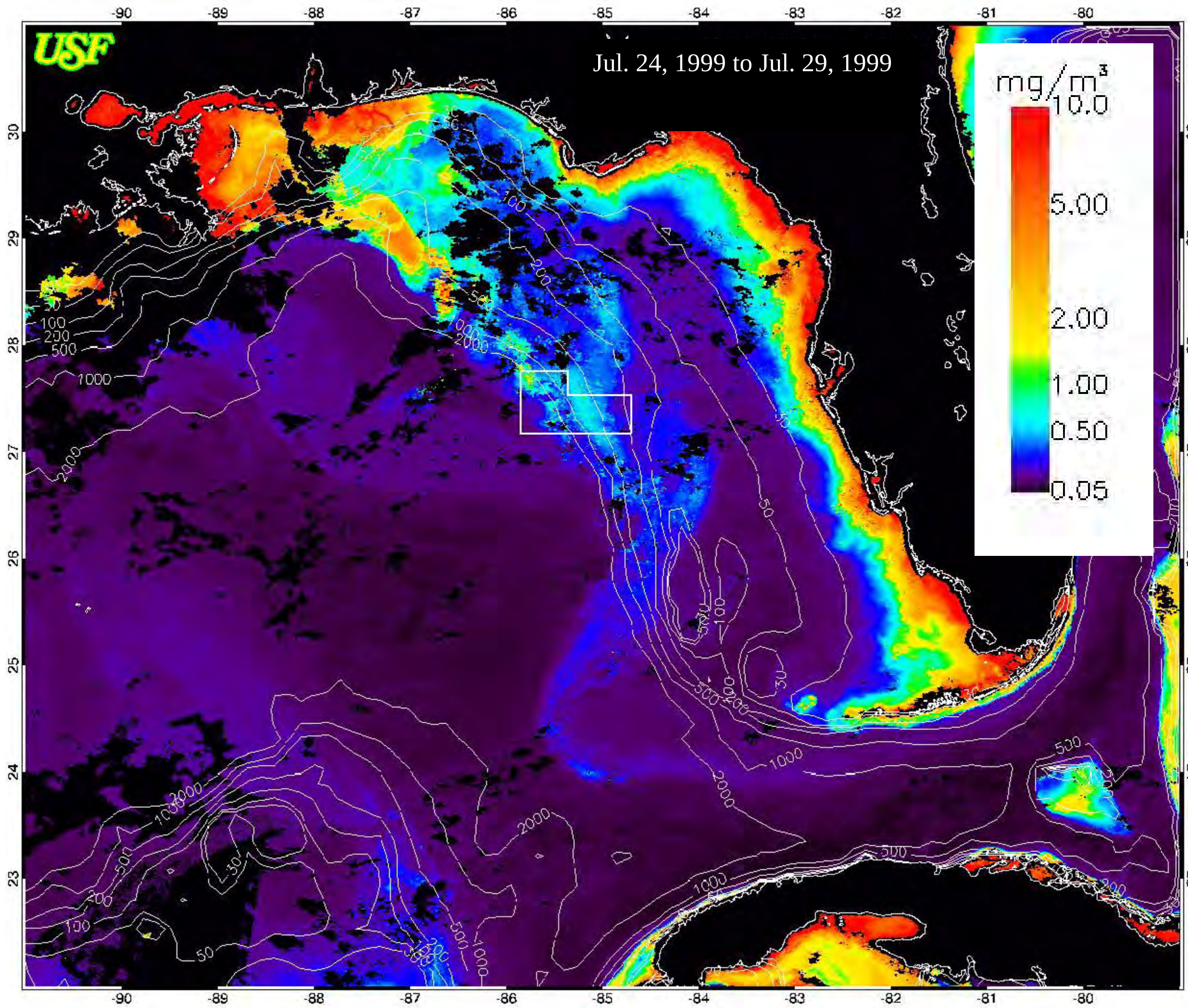


Figure 48. SeaWiFS chlorophyll composite satellite image from July 24th to July 29th, 1999. Color patterns are similar to those found in the August and September 2003 MODIS imagery, and the Mississippi water intrusion in the Florida Straits is apparent.

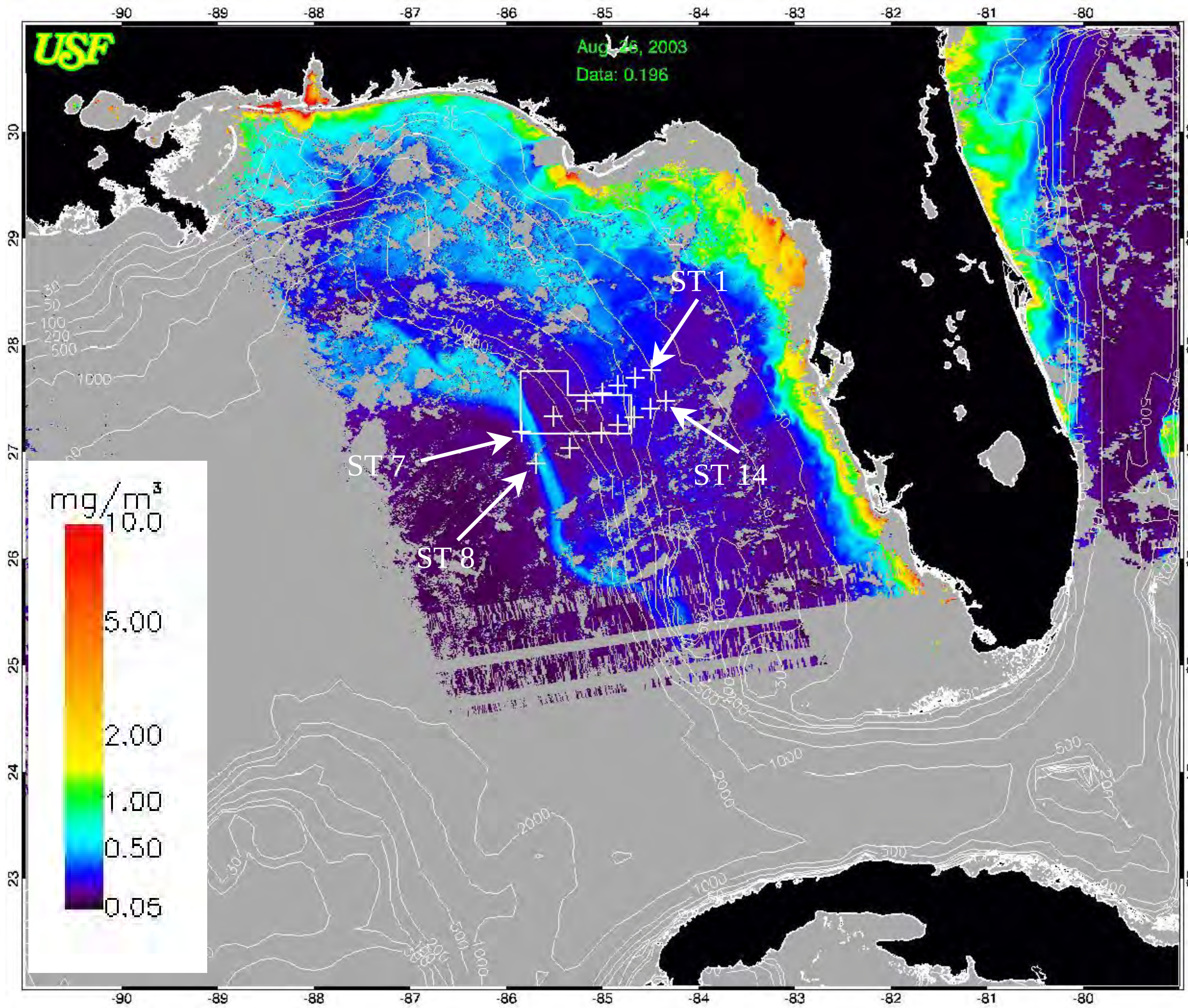


Figure 49. MODIS satellite-derived "chlorophyll" product for 26 August 2003. Overlaid on the image are the outlines (white box centered at about 27.2^{o}N 85.5^{o}W) of the dispersal area, the water depth contours (30 – 2000 m), and locations of cruise stations (from ST 1 to ST 14. Data courtesy of Danylle Spence-Ault and Gabe Vargo, USF).

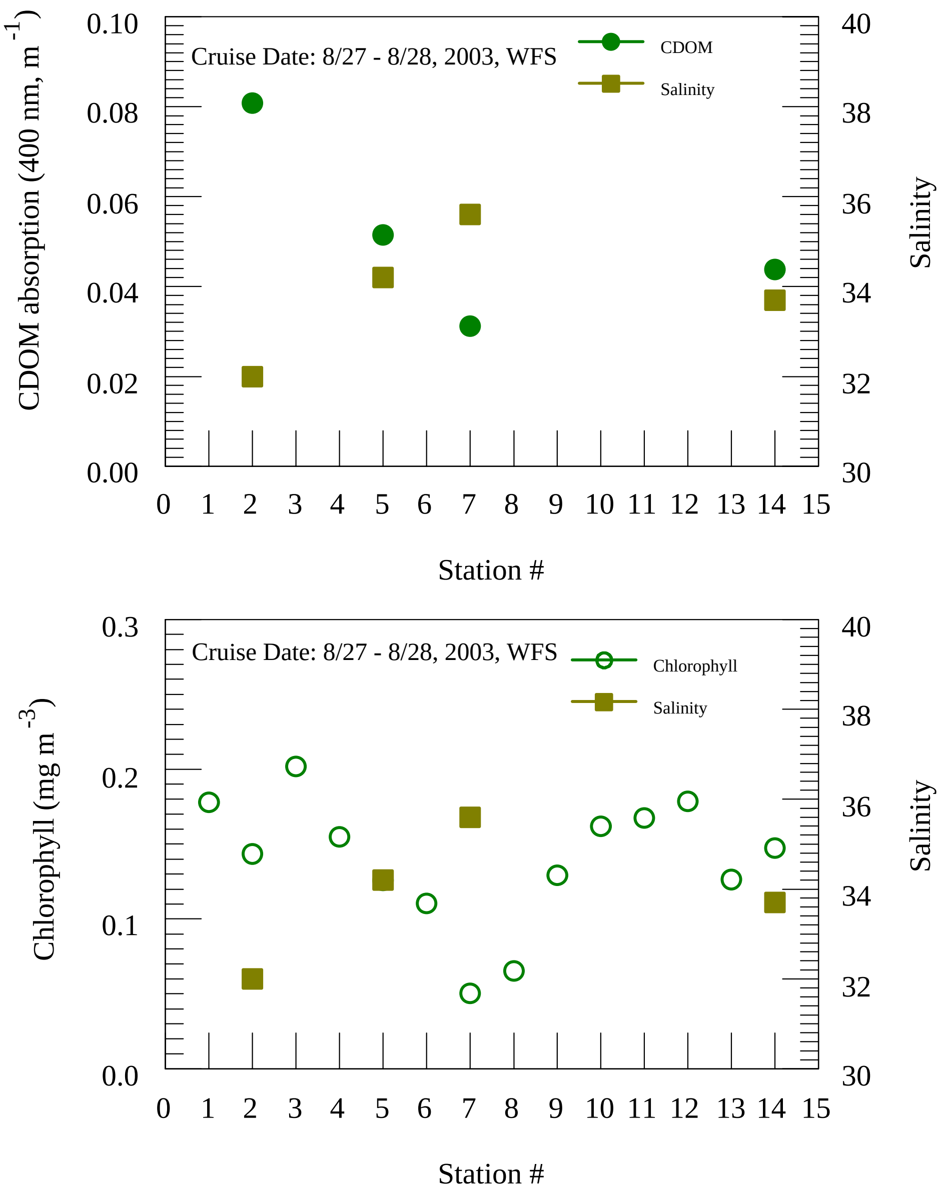
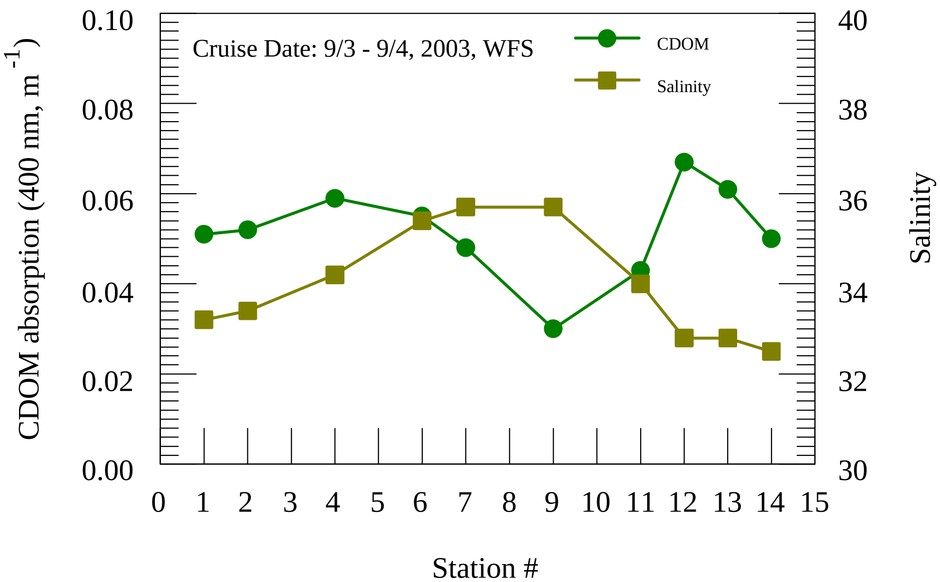


Figure 50. CDOM absorption coefficient (400 nm, m^{-1}), salinity (parts per thousand), and chlorophyll concentration (mg m^{-3}) from the surface waters of ST 1 to ST 14 (station locations shown in Fig. 49) of the 8/27 – 8/29 cruise survey (salinity and chlorophyll data courtesy of Danylle Spence-Ault and Gabe Vargo, USF).



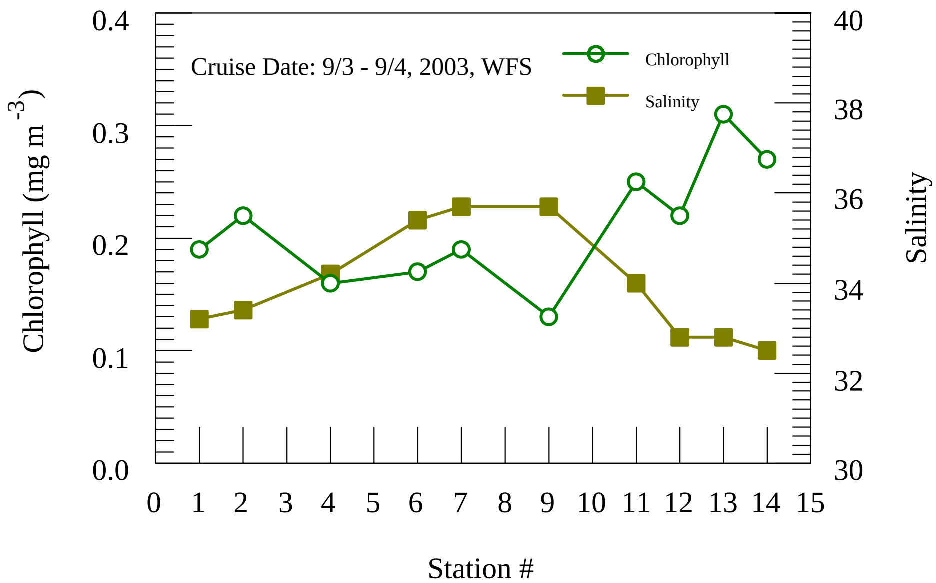


Figure 51. CDOM absorption coefficient (400 nm, m^{-1}), salinity (parts per thousand), and chlorophyll concentration (mg m^{-3}) from the surface waters of ST 1 to ST 14 (station locations shown in Fig. 49) of the 9/3 – 9/4 cruise survey (salinity and chlorophyll data courtesy of Danylle Spence-Ault and Gabe Vargo of USF).

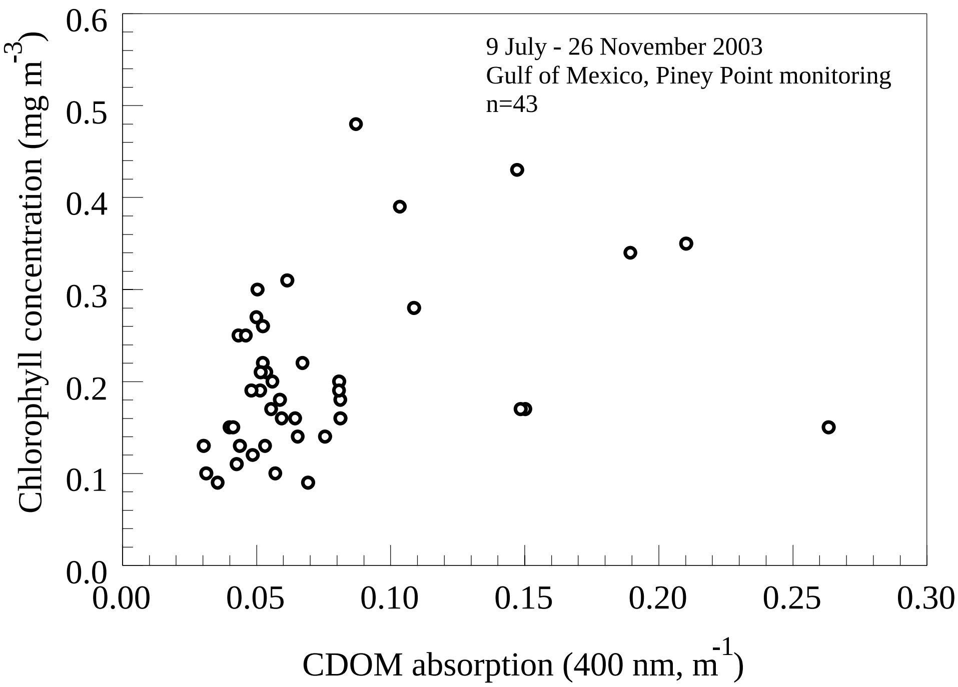


Figure 52. Comparison between surface CDOM absorption coefficient (400 nm, m^{-1}) and chlorophyll concentration (data courtesy of Danylle Spence-Ault and Gabe Vargo of USF) at some of the 14 stations (Fig. 49) from the 8 ship surveys between 9 July and 26 November 2003. The two parameters generally mimic each other, while in some cases the increases in CDOM significantly overweigh those in chlorophyll, showing typical river plume characteristics.

References

Biggs, D. C. 1992. Nutrients, plankton, and productivity in a warm-core ring in the western Gulf of Mexico. *J. Geophys. Res.* 97:2143-2154.

Carder, K. L., Chen, F. R., Lee, Z. P., Hawes, S. K., and KamyKowski, D. 1999. Semianalytic moderate-resolution imaging spectrometer algorithms for chlorophyll *a* and absorption with Bio-optical domains based on nitrate depletion temperatures. *J. Geophys. Res.* 104:5403-5421, 1999.

Esaias, W. E., et al., 1998. An overview of MODIS capabilities for ocean science observations, *IEEE Trans. Geosci. Remote Sens.*, 36, 1250-1265.

He, R., and R. H. Weisberg (2002). West Florida Shelf circulation and temperature budget for the spring 1999 transition. *Cont. Shelf. Res.* 22:719-748.

Hu, C., K. E. Hackett, M. K. Callahan, S. Andréfouët, J. L. Wheaton, J. W. Porter, F. E. Muller-Karger. 2003a. 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.

Hu, C., F. E. Muller-Karger, D. C. Biggs, K. L. Carder, B. Nababan, D. Nadeau, and J. Vanderbloemen, 2003b. Comparison of ship and satellite bio-optical measurements on the continental margin of the NE Gulf of Mexico, *Inter. J. Remote Sens.* 24:2597-2612.

McClain C. R., M. L. Cleave, G. C. Feldman, W. W. Gregg, S. B. Hooker, and N. Kuring, 1998. Science quality SeaWiFS data for global biosphere research. *Sea Tech.* **39:**10-16.

The South West Florida Dark Water Observation Group (SWFDOG), 2002. Satellite images track 'black water' event off Florida coast. *Eos. AGU Trans*. 83(26):281,285.

Vargo, G.A., C.A. Heil, D.N. Ault, M.B. Neely, S. Murasko, J. Havens, K.M. Lester, L.K. Dixon, R. Merkt, J. Walsh, R. Weisberg, and K.A. Steidinger. (in review) Four Karenia brevis blooms: A comparative analysis. Proceedings of the Xth Harmful Algal Bloom Conference, October, 2002, St. Pete Beach, FL.

Yang, H and R. H. Weisberg (1999). Response of the West Florida continental shelf circulation to climatological wind forcing, J. Geophys. Res., 104, 5301-5320.

Appendix A. Satellite instruments and image interpretation

Satellite Instruments

The satellite instruments used in this monitoring project mainly include the Sea-viewing Wide Field-of-View Sensor (SeaWiFS, http://seawifs.gsfc.nasa.gov), the Moderate Resolution Imaging Spectroradiometer (MODIS, http://modis.marine.usf.edu), and the Advanced Very High Resolution Radiometer (AVHRR, http://www.ngdc.noaa.gov/seg/globsys/avhrr.shtml). The following table lists the characteristics of these instruments.

Table 1. Satellite instruments used in the monitoring project.

Satellite	***Instrument***	***Owner***	***Measure***	***Swath (km)***	***Resolution (km)***	***Availability***
SeaStar	SeaWiFS	Orbimage	color	> 2000	~1.1	daily
Terra	MODIS	NASA	color/temperature	> 2000	~1.1	daily
Aqua	MODIS	NASA	color/temperature	> 2000	~1.1	daily
POES	AVHRR	NOAA	temperature	> 2000	~1.1	daily

These satellites instruments survey the surface ocean every day at approximately the same local time. They provide a synoptic view of the surface ocean (color and temperature) at regional to global scales. The satellite data are captured, processed, and archived by the Institute for Marine Remote Sensing (IMaRS, http://imars.usf.edu) at the College of Marine Science, University of South Florida. The algorithms used to generate these imagery data products can be found at IMaRS website http://imars.usf.edu.

Sea surface height data are obtained from the Colorado Center for Astrodynamics Research (CCAR) at the University of Colorado, Boulder (Dr. Robert Leben; http://www-ccar.colorado.edu/~realtime/gsfc_gom-real-time_ssh/). These data are used as ancillary data to help interpret the ocean features observed from the color and temperature imagery.

Online Images for Piney Point

Near real-time imagery can be found at http://imars.usf.edu/Piney_Point for public access and distribution. Note, however, while MODIS and AVHRR data are public domain, SeaWiFS data is property of Orbimage, Inc. (http://www.orbimage.com). Please contact Orbimage for any non-NASA SeaWiFS program use of data or derived imagery. Reproduction or redistribution (including media) of SeaWiFS data/imagery is prohibited without the permission or license from Orbimage.

Conventions used to name a file (image) at http://imars.usf.edu/Piney_Point are as follows:

SeaWiFS: SYYYYDDDHHMM: YYYY for year, DDD for day of the year, HH for GMT (Greenwich Mean Time) hour, MM for minutes. The images show surface chlorophyll concentrations of the ocean, as derived by the standard NASA algorithms (SeaDAS version 4.4).

MODIS: MODIS.YYYYDDD.HHMM: similar to SeaWiFS. There are several data types available for MODIS, resulted from standard NASA algorithms for MODIS, including:

surface chlorophyll concentrations, surface colored dissolved organic matter (CDOM, also called Gelbstoff) abundance, surface temperature, and red-green-blue (RGB) composite images.

AVHRR: nNN.YYYYDDD.HHm: NN for NOAA satellite number, MM for month, DD for day, HH for GMT hour, mm for minutes. The images show sea surface temperature.

Color interpretation of satellite images

It is important to note that by no means do the colors shown on the images reflect the actual color of the ocean. Instead, they simply represent various relative concentrations of water constituents. The color-concentration relationship can be found on a color legend, but please note caveats provided below. RGB composite imagery does reflect the real color of the ocean, but only to some extent.

Various constituents in both particulate and dissolved forms determine ocean color. In the open Gulf the color is generally dominated by phytoplankton, the living, tiny organisms which serve as the base of the food chain. In waters where coastal runoff (river discharge and other terrestrial runoff) is significant the color is a mixture of phytoplankton, dissolved matter, and suspended inorganic particles (clay, sediments, etc.) where any of these species can dominate the color.

The chlorophyll images (with "florida" in the SeaWiFS filenames and with "chlor" in the MODIS filenames) show the surface concentration (in milligrams per cubic meter) of phytoplankton pigment, chlorophyll-*a* (the photosynthetic pigment that also exists in all green tree leaves). High values are indications of biologically active waters. The values are more accurate for open Gulf waters without river intrusion than for coastal waters or river plume waters. Indeed the yellow-red colors seen off the coasts reflect not only chlorophyll but also dissolved matter and suspended sediments (i.e., they are often overestimates of the real chlorophyll concentrations). The river plume band seen offshore in the Gulf of Mexico may contain high concentrations of colored dissolved organic matter, as well as variable amounts of plankton.

The temperature images show the surface temperature of the ocean. Different temperatures are represented by different colors (see color legend). Waters of various origins sometimes display different colors. For example waters from the tropics often show higher temperatures than the Gulf water.

IMaRS Disclaimer

The use of the images should be credited to IMaRS, NASA SeaWiFS and MODIS Projects, NOAA, and OrbImage. The images are provided by IMaRS on an "as is" basis and IMaRS is not responsible for any interpretation by any users other than those provided by IMaRS personnel, who use these images in research mode – interpretation is subject to error in the data and scientific uncertainty. The IMaRS Piney Point website (http://imars.usf.edu/Piney_Point) may be removed upon completion of the FDEP Piney Point discharge project. Orbimage has graciously permitted us to publish SeaWiFS images periodically (not routinely) for demonstration purposes. However, further publication or redistribution of SeaWiFS data/imagery is prohibited without proper authorization from Orbimage, Inc.

Appendix B. Accuracy of Satellite Measurements

All satellite-derived parameters are subject to some degree of uncertainty, which varies from sensor to sensor. While sensor specifications called for uncertainties ±0.5°C for sea surface temperature (SST) and ±35% for surface chlorophyll concentration, such specifications cannot always be met.

In general, SST derived from AVHRR sensors meet the ±0.5°C uncertainty under most circumstances (Hu et al., 2003b), and chlorophyll derived from SeaWiFS (NASA standard algorithms from SeaDAS4 software package) meet the 35% criteria for clear waters without river plume interference. Application of the Carder et al. (1999) algorithm leads to some degree of improvement in river plumes, yet larger than ±35% uncertainty still exists (Hu et al., 2003b). Figure 53 shows the comparison between SeaWiFS-derived chlorophyll (Carder et al. algorithm) and chlorophyll obtained from eight ship surveys (data courtesy of Gabe Vargo and Danylle Spence-Ault, USF). The surveys were conducted around 9 July, 28 July, 18 August, 27 August, 3 September, 1 October, 12 November, and 24 November, respectively, at the pre-selected fourteen stations (Figure 49). In this comparison, the SeaWiFS data were selected only if the SeaWiFS measurement was within ±12 hours of the ship survey. Due to frequent cloud cover and other factors (e.g., satellite viewing angle is too large to result in high-quality data), only 25 matching pairs were found (ideally there should be $8 \times 14 = 112$ pairs). The figure shows that the overall agreement is satisfactory, with a few points having differences > ±35%. Note, however, such differences may not indicate error, as the satellite and ship measurements were not strictly at the same time and location (a ship water sample was from one point, while a satellite point represents ~ 1 km^2). Although some water samples were analyzed for their CDOM content, there were too few matching pairs, due to cloud cover and different measurement times between satellite and ship survey, to result in meaningful comparison. However, with the Carder et al. (1999) algorithm, the uncertainty in CDOM estimates from SeaWiFS is believed to be similar to that for chlorophyll (Hu et al., 2003b). The high quality of SeaWiFS data, resulting from enormous amount of community efforts in sensor calibration/characterization and algorithm development, makes quantitative estimates of any changes possible, except in very turbid coastal and river plume waters.

MODIS real-time data, on the other hand, are of provisional quality, due primarily to uncertainties in sensor calibration/characterization. However, as we have demonstrated in the report series, they are extremely useful in studying the circulation features and documenting any anomaly phenomena for at least three reasons: 1) MODIS data are public domain; 2) MODIS data have extremely high sensitivity that can be used to detect subtle features which are difficult or impossible to detect by ship surveys; 3) A combination of MODIS/Terra (morning pass) and MODIS/Aqua (afternoon pass) provides nearly 100% more coverage than SeaWiFS in terms of reduced cloud cover for the area bounded by 22° to 31°N and 91° to 79°W (Figure 54). MODIS chlorophyll data were used in this monitoring project to recognize features and to document the circulation patterns only.

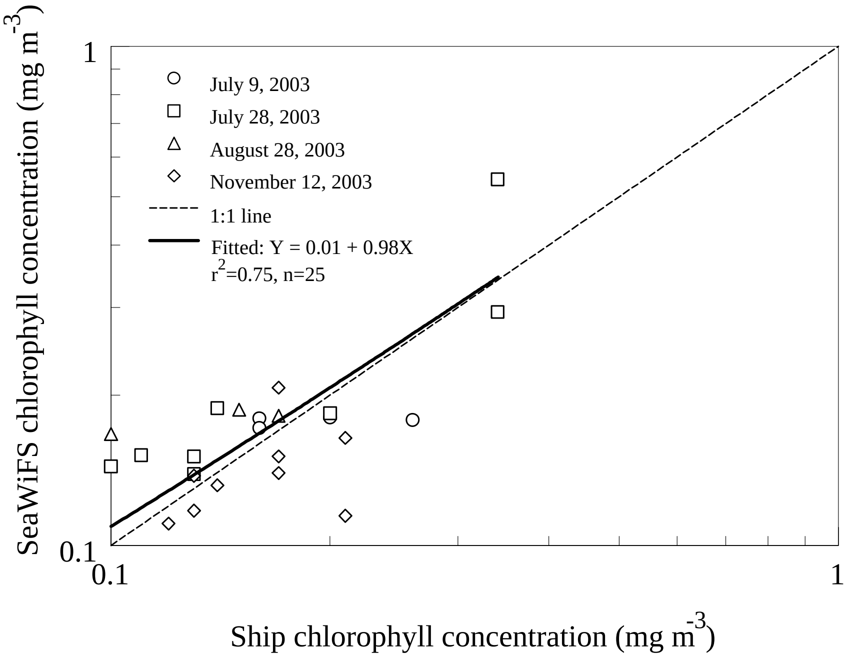


Figure 53. Comparison between SeaWiFS-derived surface chlorophyll concentrations (Carder et al. 1999 algorithm) and those from ship survey (data courtesy of Gabe Vargo and Danylle Spence-Ault, USF) for the eight ship surveys between early July and late November 2003. Of the potential 112 data pairs only 25 were found as concurrent (within ±10 hours) and free of cloud cover.

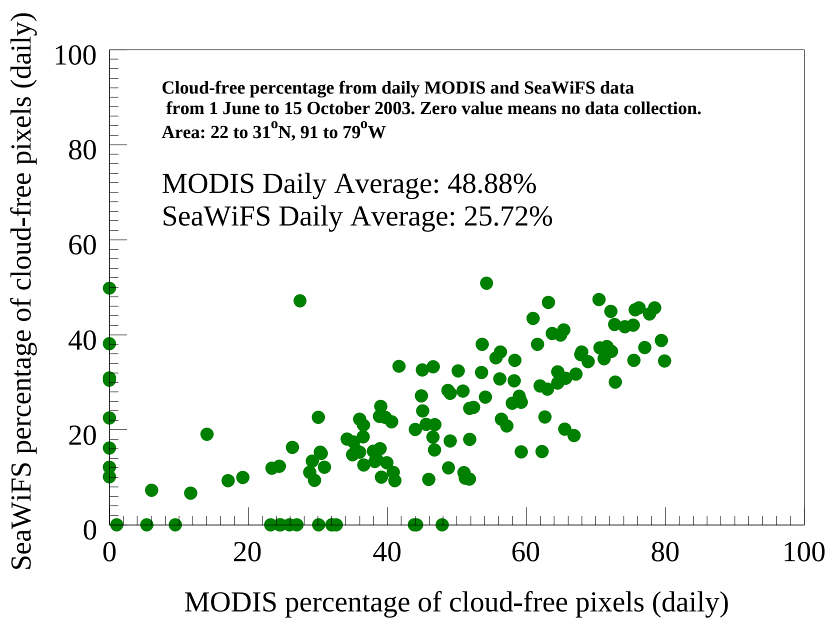


Figure 54. Percentage of cloud-free pixels of SeaWiFS and MODIS daily imagery from 1 June to 15 October 2003 for the area of 22° to 31°N and 91° to 79°W. In a few cases SeaWiFS has more coverage than MODIS; this is because that the MODIS data for those days were from another antenna at GSFC (the USF antenna was down due to lightening) therefore the southern part of the area was not covered.