

LONGEVITY AND EXTENT OF TROPICAL-STORM INDUCED PLUMES DETECTED FROM SATELLITE DATA

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Abstract

The impact of tropical storms on coral reefs can be both immediate and lingering. Satellites can provide synoptic coverage of storm-induced plumes of sediment and associated runoff, whose effects are proportional to the length and extent of the plume. We examined three hurricanes (Andrew, Georges and Charley) affecting south Florida utilizing three different satellite sensors (Landsat, SeaWiFS and MODIS) to determine what information these sensors could provide. Results show all three sensors could provide some information on the longevity and geographic extent of the plumes. However, usefulness of the satellite data was limited by the amount of cloud cover. The storm-induced plumes observed lasted four to seven days and stretched as far as 120 km.

Introduction

Tropical storms can cause immediate, negative impacts on shallow water habitats, including coral reefs (Hughes and Connell, 1999; Kleypas et al., 2001). Physical damage can occur on small (individual corals) to larger (entire coral spurs) scales as an immediate response to current and wave action from tropical storms. This can occur even if the eye of the tropical storm passes hundreds of kilometers away. Hurricane Dennis (2005) shifted the Spiegel Grove, a 510 foot naval ship sunk as an artificial reef off Key Largo, from its starboard side to upright, though the eye of the storm passed more than 200 km west of the ship. Physical breakage, specifically to branching corals (i.e., *Acropora* spp.), was also noted after this storm. Broken fragments settled in the lee of the reef crest where the live coral tissue gradually died off (Fig. 1a). The remaining base (Fig. 1b), which may have become stressed, could succumb to disease or bleaching (Hughes and Connell, 1999).

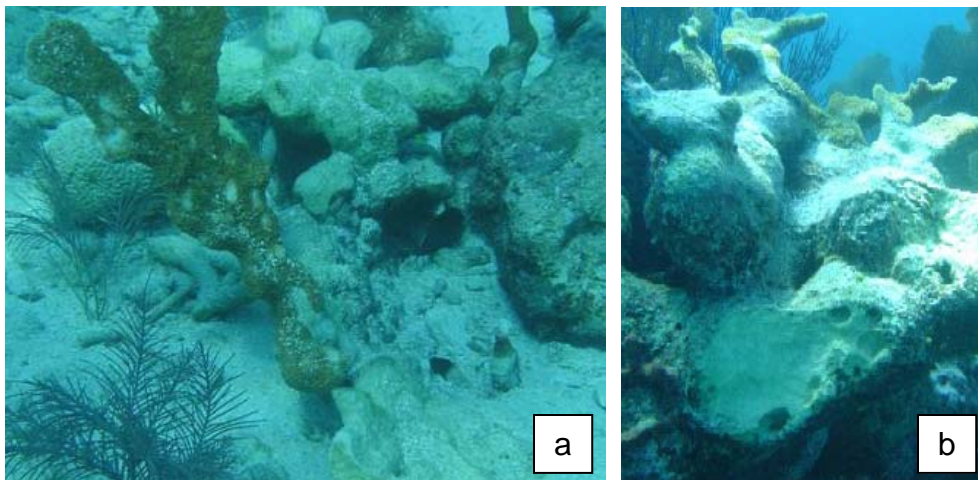


Figure 1. Physical breakage caused by Hurricane Dennis (2005) from Key Largo Dry Rocks, Florida, *Acropora* (a) fragment and (b) base.

Hurricanes are a natural part of the global climate. However, with ever increasing human populations along tropical coastlines, the indirect effects of tropical storms on benthic resources in the days to months following tropical storms can be far from expected (e.g., Timant et al., 1994; Andréfouët et al., 2002). These effects include increased turbidity as a result of sediment and pollutant runoff, which are directly linked to overpopulation and consequent destruction of forest and groundcover within the watershed. Storm plumes can vary in size and duration depending on the characteristics of each storm and immediate climate and oceanic state (e.g., Andréfouët et al., 2002). The potential for lingering effects of nutrient and pollutant runoff and increased sediment in the water column are proportional to temporal and spatial extent of each plume.

This study utilizes three different satellite sensors to study three hurricanes that occurred over south Florida (Key Biscayne to the Dry Tortugas); Hurricane Andrew (1992), Hurricane Georges (1998) and Hurricane Charley (2004). This was done to determine if data on the geographic extent and longevity of tropical storm-induced plumes can be ascertained from the satellite data.

Satellite Information

This study utilizes three satellite sensors; Landsat 5 Thematic Mapper (TM), the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and the Moderate Resolution Imaging Spectroradiometer (MODIS) (Table 1). All three sensors provide data in the visible (VIS) and infrared (IR) range. Landsat 5 TM and MODIS can also provide information on sea-surface temperature (SST). Both SeaWiFS and MODIS are primarily used as ocean color sensors with a spatial resolution (i.e., pixel size) of 1 km. Landsat 5 TM, and its follow-on mission Landsat 7 Enhanced Thematic Mapper Plus (ETM+), are used primarily for terrestrial and coastal studies. There are benefits and downsides to each of the sensors. For example, Landsat data provide information at the 30 m spatial resolution but only every 16 days. MODIS and SeaWiFS provide data daily but at 1 km spatial resolution.

Table 1. Information on satellite sensors utilized here.

Satellite / Sensor	Spatial Resolution (VIS)	Temporal Resolution	Operation Status
SeaStar / SeaWiFS	1 km	Daily	1997 to present
Terra and Aqua / MODIS	500 m and 1 km	2x day	2001 to present
Landsat 5 / TM	30 m	16 days	1984 to present

Methods and Materials

Hurricane Andrew

Hurricane Andrew passed over Biscayne Bay 24 August 1992. Two Landsat 5 TM images were obtained from the US Geological Survey EROS Data Center, pre-(17 August 1992) and post-(4 October 1992) hurricane. The VIS data (bands 1-3) were processed with ENVI® image processing software to produce red-green-blue (RGB) true color images in order to determine water column clarity.

Hurricane Georges

Hurricane Georges passed over the Florida Keys 25 September 1998. SeaWiFS chlorophyll concentration-derived images from 22 – 29 September 1998 were used as a proxy for possible nutrient availability. The operating assumption is because phytoplankton require nutrients to photosynthesize, higher chlorophyll concentrations may be linked to greater availability of nutrients (Kirk, 1984). The images were provided by the Institute for Marine Remote Sensing (IMaRS) located at the College of Marine Science, University of South Florida.

Hurricane Charley

Hurricane Charley passed over the Dry Tortugas 13 August 2004. MODIS RGB imagery, provided by IMaRS, from 11 – 21 August 2004 was processed within ENVI® to determine time and extent of the sediment plume produced.

Results and Discussion

Hurricane Andrew

There was difficulty in acquiring a Landsat image immediately after 24 August 1992 (hurricane landfall) due to high cloud cover. Although three Landsat images were acquired by the satellite between 24 August and 3 October, all contained cloud cover of 80% or more over the Biscayne Bay area. This led to the utilization of the 4 October 1992 image. Although 41 days after the event, the post-hurricane image clearly shows water column turbidity. This becomes especially striking when compared to the pre-hurricane image (17 August 1992) (Fig. 2). The margin reef tract, visible in the pre-hurricane image, is completely obscured by the water column in the post-hurricane image. Even the shallow water seagrass beds shown in Fig. 2 (subset 3) appear ‘washed out’ by the water column. Blair et al. (1994) observed a dramatic decline in benthic cover due to Hurricane Andrew using *in situ* and photogrammetric methods. However, as the benthos is not detectable through the water column, this cannot be documented as part of this study

There is no direct evidence that the effects of Hurricane Andrew caused the water column to remain mixed for 41 days after its passing, although Timant et al. (1994) did observe ‘poor water quality’ during their surveys of Biscayne Bay on 16 – 19 September 1992. The NOAA C-MAN station located at Fowey Rocks stopped acquiring wind data at 0800 the day of the storm with winds recorded at 56.4 knots. Unfortunately, the station did not become operational again until 31 March 1993. Therefore it is difficult to determine if the high turbidity seen in the post-hurricane Landsat image is indeed a lingering effect of Hurricane Andrew or from another, less-significant, wind event occurring in the time frame just before the image was acquired. It can be argued that in either case, Hurricane Andrew provided the availability of fine sediments to be reintroduced into the water column 41 days after it had passed.

Hurricane Georges

Chlorophyll-derived SeaWiFS images from before (22 September 1998) and after (29 September 1998) Hurricane Georges (25 September 1998) (Fig. 3) show an increase in chlorophyll post-hurricane for points randomly selected inside (4) and outside (3) of

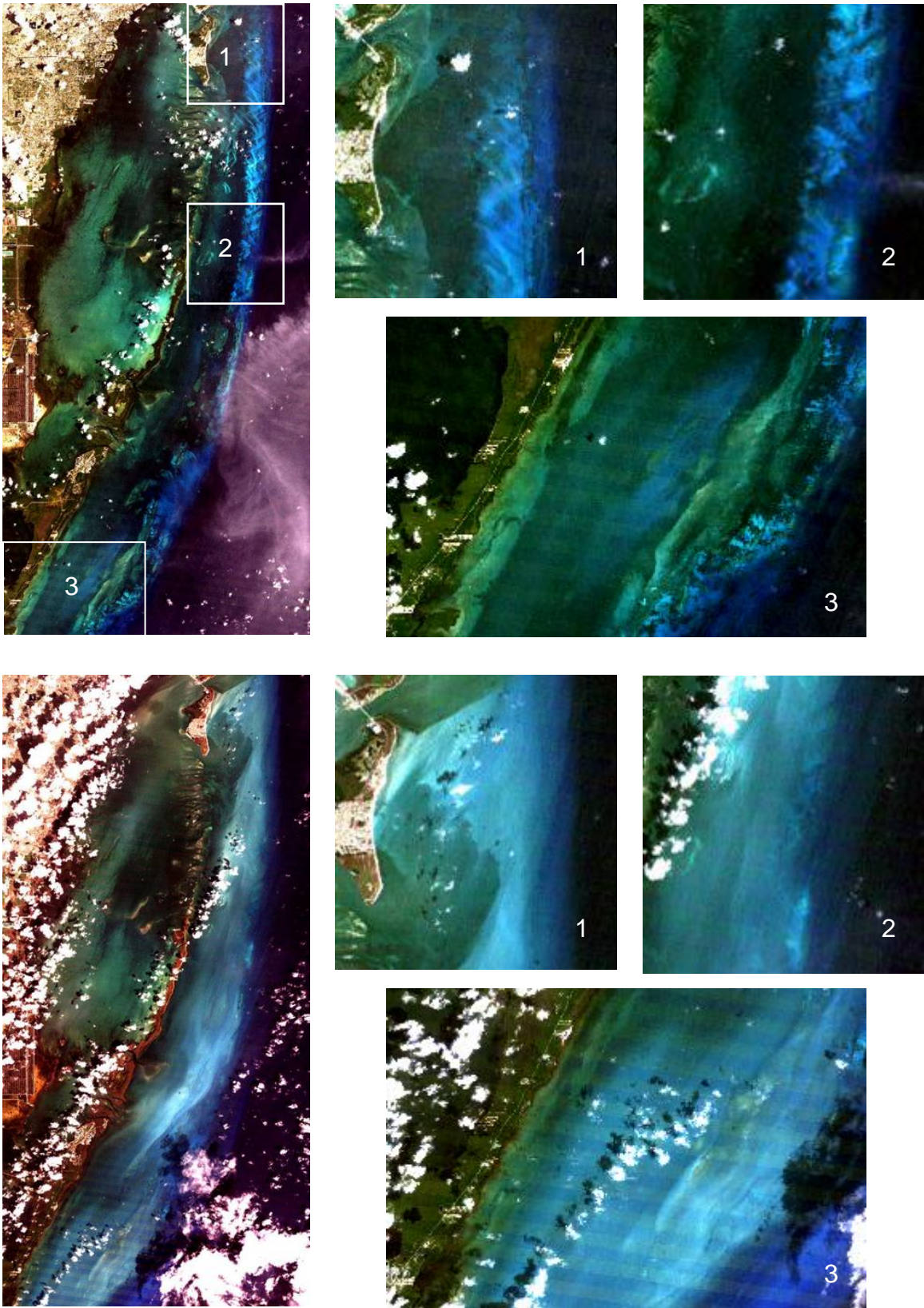


Figure 2. Landsat 5 TM images of Biscayne Bay acquired before (17 August 1992, top) and after (4 October 1992, bottom) Hurricane Andrew. Zoom images are shown and labeled respectively.

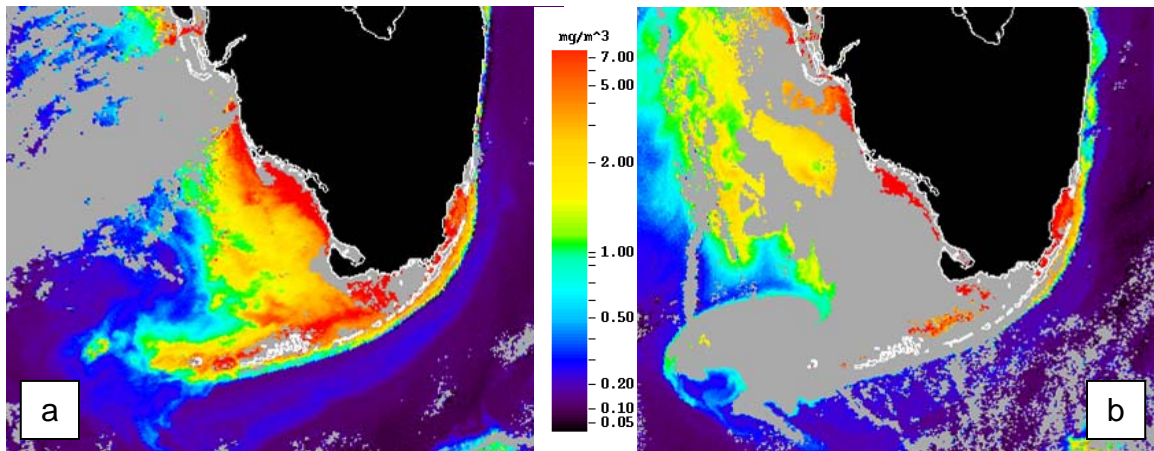


Figure 3. Chlorophyll concentration-derived SeaWiFS imagery of south Florida from before (22 September 1998, a) and after (25 September 1998, b) Hurricane Georges. Land mask is shown in black and cloud mask is shown in grey.

Biscayne Bay (Table 2). It would have been preferable to study the area near the landfall of Hurricane Georges, near Marathon, FL (Middle Keys). Unfortunately as Figure 3 shows, very little data can be obtained in this area inside the outer reef tract, due to heavy cloud cover (shown in grey). All randomly-selected points in and around Biscayne Bay were higher post-hurricane. The average chlorophyll value pre-hurricane was 4.00 mg/m^3 , compared to a post-hurricane value of 5.22 mg/m^3 . This may provide evidence that Hurricane Georges stimulated phytoplankton growth by increasing nutrient availability. Both runoff from land and the suspension of sediments and nutrient-laden interstitial waters can temporarily increase nutrient availability and thereby trigger an algal bloom. Lawrence et al. (2004) found an increase in nutrient availability and subsequent increase in chlorophyll concentration in Florida Bay due to a wind-mixing event. Similar data were used by Acker et al. (2004) to derive the amount of sediment mass transport after two hurricane events for the Caribbean.

Table 2. Chlorophyll concentrations (mg/m^3) derived from SeaWiFS before (22 September 1998) and after (29 September 1998) Hurricane Georges. Measurements were taken in and around Biscayne Bay, * denote those values outside.

Latitude	Longitude	Before [CHL]	After [CHL]
25.6523	-80.2010	6.45	8.46
25.5531	-80.2210	5.77	7.39
25.4990	-80.2210	4.39	4.52
25.4810	-80.2611	4.39	6.27
*25.5531	-80.1910	4.52	7.00
*25.6072	-80.1109	2.11	2.77
*25.4990	-80.1009	0.38	1.55

Hurricane Charley

MODIS RGB imagery from 15 August 2004 (Fig. 4b) shows a significant sediment plume located north of the Dry Tortugas (seen as a bright area surrounded by open water). This plume is not visible in the pre-hurricane image acquired two days earlier

(Fig. 4a). The plume measures approximately 120 km (north-south). The size diminishes significantly by 18 August (Fig. 4c) and is no longer visible by 21 August (Fig. 4d). These data indicate a plume longevity of approximately seven days, from production by hurricane activity to dispersal of the plume.

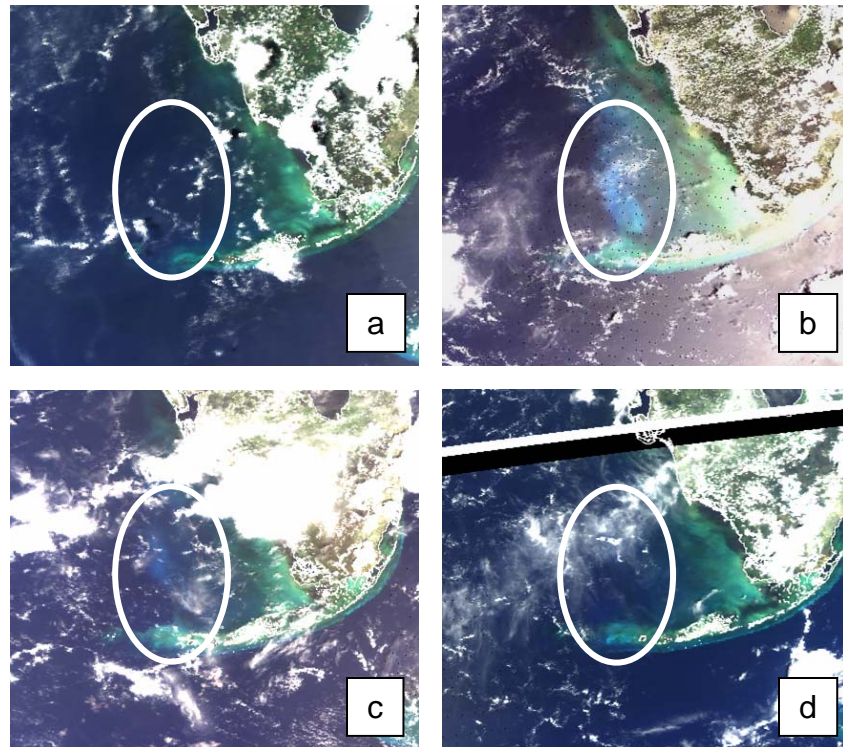


Figure 4. MODIS RGB imagery showing the before and after progression of the sediment plume produced by Hurricane Charley, starting 11 August 2004 (a), 15 August 2004 (b), 18 August 2004 (c) and 21 August 2004 (d). White oval highlights area of plume.

Conclusions

These results demonstrate both the usefulness and the short comings of satellite data as a tool for monitoring hurricane impacts on marine communities. There is a great potential to use such data to determine both the longevity and extent of storm-induced plumes. However, visible satellite data and visible satellite derived data (i.e., ocean color) require clear skies, i.e., little to no cloud cover over the target area of interest. In the case of Hurricane Andrew, for which Landsat data was used to look for turbidity plumes, there was a lag of 41 days post-event before skies were sufficiently clear to acquire useable images. MODIS and SeaWiFS can provide as many as three images per day, and therefore greater probability of useful images. Unfortunately, these images lack the spatial resolution to provide water column information at the habitat scale of coral reef environments.

SeaWiFS and MODIS provided daily imagery for Hurricanes Georges and Charley, respectively. Storm-induced plumes of four to seven days, respectively, were successfully documented. The geographic extent of a plume was only accurately determined from the MODIS data for Hurricane Charley.

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