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Storm-induced injection of the Mississippi River plume into the open Gulf of Mexico

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[1] The direct impact of the Mississippi River on the open Gulf of Mexico is typically considered to be limited due to the predominantly along-shore current pattern. Using satellite imagery, we analyzed *chl a* distributions in the northern Gulf of Mexico before and after the passage of two storms: Hurricane Lili and Tropical Storm Barry. Our analyses indicate that storm-induced eddies can rapidly inject large volumes of nutrient-rich Mississippi River water to the open gulf, and lead to phytoplankton blooms. Although these events last only a few weeks, they transport significant amounts of fluvial substances to the ocean. These river-ocean interactions are especially significant in tropical and subtropical regions because receiving waters are typically permanently stratified and oligotrophic. *INDEX TERMS:* 4520 Oceanography: Physical: Eddies and mesoscale processes; 4219 Oceanography: General: Continental shelf processes; 4275 Oceanography: General: Remote sensing and electromagnetic processes (0689); 4243 Oceanography: General: Marginal and semienclosed seas; 4855 Oceanography: Biological and Chemical: Plankton. **Citation:** Yuan, J., R. L. Miller, R. T. Powell, and M. J. Dagg (2004), Storm-induced injection of the Mississippi River plume into the open Gulf of Mexico, *Geophys. Res. Lett.*, *31*, L09312, doi:10.1029/2003GL019335.

1. Introduction

[2] The Mississippi River, the largest river in North America, drains more than 40% of the conterminous United States and stretches over 3000 km from Minnesota to southern Louisiana [*Milliman and Meade*, 1983]. In comparison to seawater, river water contains orders of magnitude higher concentrations of dissolved organic carbon [*Guo et al.*, 1999], nutrients [*Turner and Rabalais*, 1994], trace metals [*Shiller*, 1997], and suspended sediments [*Milliman and Meade*, 1983], and therefore could be a major source of material to the Gulf of Mexico. The northern Gulf of Mexico however, is characterized by a seasonally shifting eastwards or westwards along-shelf surface current [*Walker*, 1996; *Wiseman et al.*, 1997; *Nowlin et al.*, 1998] which limits the exposure of the river plume to the open gulf and restricts river impacts to the continental shelf. Therefore, discharge from the Mississippi River plume is usually confined to coastal regions of the northern Gulf of Mexico [*Wiseman et al.*, 1997]. Effects of fluvial flux on dissolved organic carbon [*Guo et al.*, 1999], nutrients [*Turner and Rabalais*, 1994], trace metals [*Shiller*, 1997], *chl a* [*Chen et al.*, 2000], and primary productivity [*Chen et al.*, 2000] are typically detected only in near shore regions. The direct impact of the Mississippi River on the chemical mass balance and biological productivity of the open Gulf of Mexico has not been well documented.

[3] In contrast to the highly productive river dominated shelf, the open Gulf of Mexico is permanently stratified, subtropical and oligotrophic. The general circulation of the Gulf of Mexico is dominated by the Loop Current (Figure 1a) which enters the Gulf through the Yucatan Straits, loops clockwise through the southeastern Gulf, and exits through the Straits of Florida [*Leipper*, 1970]. The Loop Current evolves from the "young state" when it is hugging the northern coast of Cuba, to the "mature state" when it penetrates northward as seen in Figure 1a, and then shifts back to the "young state" by shedding off an anticyclonic eddy [*Hetland et al.*, 1999]. Such eddies usually move west through the central Gulf of Mexico (Figure 1a). On average, 1.5 hurricanes or tropical storms impact the gulf coast states annually [*Neumann et al.*, 1987] but their effects on the river-ocean interaction and the Gulf of Mexico marine ecosystem are not well known. We analyzed satellite monitored patterns of sea surface chlorophyll *a*, sea surface height (SSH) anomalies, and the surface currents deduced from SSH anomalies for the northern Gulf of Mexico during Hurricane Lili of 2002 and Tropical Storm Barry of 2001. Both storms led to significant changes in the patterns of these properties in the northern Gulf of Mexico, resulting in the injection of river water into the open Gulf of Mexico and a phytoplankton bloom in the open sea.

2. Data and Methods

[4] SeaWiFS data were obtained from NASA's Distributed Active Archive Center (DAAC). For this study, Local-area-coverage (LAC) level 1A (L1A) data with 1 km resolution were processed to level 2 using the SeaDAS software [*Fu et al.*, 1998]. Sea surface *chl a* concentrations were calculated using the OC4 algorithm [*O'Reilly et al.*, 1998]. Sea surface height (SSH) anomaly and surface current data were obtained from the Colorado Center for Astrodynamics Research (CCAR) of the University of Colorado. The data set was generated from model mean and altimeter measurements from the TOPEX/Poseidon and ERS-2 satellites by CCAR [*Le Traon and Morrow*, 2000].

3. Results

[5] Generally, the broad scale physical structure of the Gulf of Mexico was similar before both storms. There were

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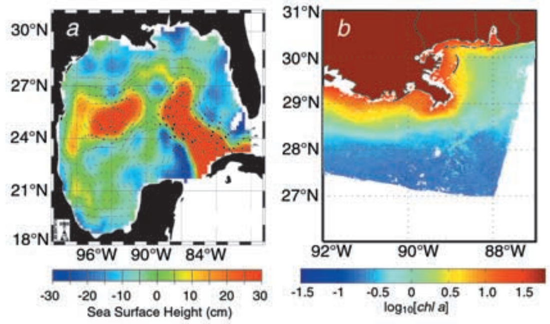

Figure 1. A typical distribution of sea surface height (SSH) anomaly, surface current, and sea surface *chl a* before the passage of the Tropical Storm Barry or Hurricane Lili. The SSH and surface current for August 1, 2001 is shown (a). The sea surface *chl a* (μg/l) annual mean of between July 2001 and June 2002 is shown (b).

two major positive SSH anomalies, one at the center of the Loop current in the southeast and the other in the west central Gulf Mexico (Figure 1a). These positive SSH anomalies were the centers of anticyclonic eddies characterized by clockwise circulating currents. Impacts of SSH anomalies on the shelf were relatively small and shelf currents flowed along-shore in the northern Gulf of Mexico. The distribution of *chl a* before each storm was similar to its annual mean which is characterized by a coastal maximum and decreasing concentrations offshore (Figure 1b). This *chl a* pattern is consistent with along-shore currents and the along-shore dispersion of fluvial nutrients [*Walker*, 1996; *Wiseman et al.*, 1996; *Nowlin et al.*, 1998].

[6] The passage of Tropical Storm Barry and Hurricane Lili significantly altered the pattern of SSH anomalies in the northern Gulf of Mexico. This is reflected by the generation of an eddy to the southwest of the Mississippi River delta. The eddy likely resulted from interaction of the delta and a northward boundary current, as shown by laboratory experiments [*Cenedese and Whitehead*, 2000] and numerically modeling [*Zamudio et al.*, 2002]. *Cenedese and Whitehead*'s [2000] experiments also showed eddies would be generated southwest of the delta.

3.1. Tropical Storm Barry

[7] Tropical Storm Barry originated in the eastern Gulf of Mexico on August 2, 2001, moved northwestwards for two days to a point ~200 km directly south of Alabama, turned northeastwards on August 5, and made landfall near Destin, Florida on the morning of August 6 (Figure 2a). The storm had maximum sustained winds of 110 km h^{-1}, caused a 1.5 to 4 m storm surge, and deposited 13 to 25 cm of rain in the coastal regions.

[8] The interaction between the Mississippi River delta and the boundary currents induced by Tropical Storm Barry caused a positive SSH anomaly (90°W, 28°N) and consequently an eddy with clockwise circulating surface currents near the mouth of the Mississippi River (Figure 2b). As a result, shelf currents flowed southwards to the east and northwards to the west of the SSH anomaly, which led to the injection of Mississippi River plume water into the open gulf. This physical structure persisted for about two weeks (images not shown), resulting in the transport of significant amounts of fluvial nutrients and other dissolved and particulate materials to the open gulf.

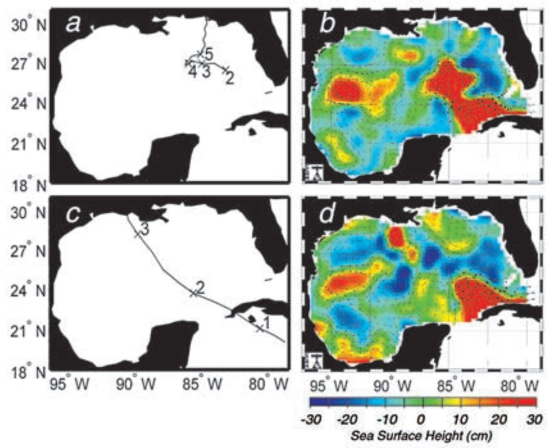

Figure 2. The path of Tropical Storm Barry (a) and Hurricane Lili (c), and a typical pattern of sea surface height anomalies after Barry (08-16-2001 is shown) (b) and Lili (10-08-2002 is shown) (d). The line represents the path, while the number shows the location of the eye on the date of the month (August 2001 for Barry and October 2002 for Lili).

[9] This injection of plume water can be seen in the time series of satellite-derived *chl a* (Figure 3). On August 9, three days after the storm made landfall east of the Mississippi River delta, a "tongue" of high *chl a* appeared to the south of the delta. The next few days were too cloudy for the satellite sensor. By August 16, the *chl a* pattern indicated that the "tongue" had extended southeastward and made a further extension to the southwest. The "tongue" extended farther west by August 17, northwestward by August 18, and northward and eastward by August 19 to become a loop or ring of high *chl a* water surrounding a large central region of low *chl a* water. The ring was approximately 30 km wide and 300 km in circumference. The concentration of *chl a* was as high as 10 μg/l on the axis

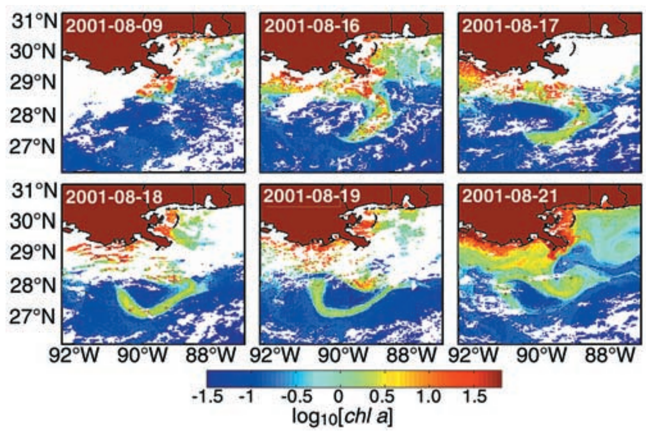

Figure 3. Evolution of sea surface *chl a* in the northern Gulf of Mexico after the passage of Tropical Storm Barry. *Chl a* concentrations (μg/l) were calculated from the SeaWiFS LAC data using the standard SeaDAS algorithm (OC4).

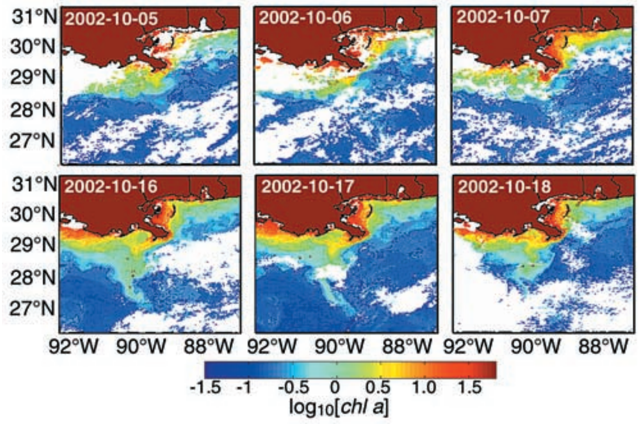

Figure 4. Same as Figure 3 but after the passage of Hurricane Lili.

of the "tongue". From August 21 onwards, *chl a* concentration in the southern half of the ring gradually diminished.

3.2. Hurricane Lili

[10] The passage of Hurricane Lili also altered the pattern of SSH anomalies in the northern Gulf of Mexico. Hurricane Lili formed in the Caribbean in late September 2002. It took a northwestward course in the weeks that followed, strengthened to a Category 4 hurricane in the northern Gulf of Mexico, weakened near the Louisiana coast and made landfall near Vermilion Bay, Louisiana, on the morning of October 3, 2002 (Figure 2c). The hurricane had maximum sustained winds of 160 km h^{-1}, caused a 1.5 to 3 m storm surge, and deposited as much as 12 cm of rain in the coastal regions. The hurricane followed a similar course to that of tropical storm Isidore, which made landfall in southern Louisiana a week before.

[11] The interaction between the Mississippi River delta and boundary currents induced by Hurricane Lili generated an elliptical positive SSH anomaly and an associated eddy with clockwise circulating surface currents near the mouth of the Mississippi River (Figure 2d). The shelf currents east of the SSH anomaly flowed southward and led to the injection of the Mississippi River plume water to the open gulf. This SSH anomaly also persisted for about two weeks (images not shown) and led to significant injection of fluvial nutrients and other dissolved and particulate materials to the open Gulf of Mexico.

[12] The injection of the plume water by Hurricane Lili can be seen in the time series of *chl a* images (Figure 4). On October 5, 2002, two days after the passage of Hurricane Lili, a slight southward injection of the Mississippi River plume was observed. On the following two days, the river plume moved slightly southward. Between October 8 and 15, conditions were too cloudy for the satellite sensor. By October 16, the river plume had penetrated south of 27°N. The river plume persisted in the region for the next two days and dispersed gradually thereafter.

4. Discussion

[13] Mechanisms of eddy formation have been the focus of several recent laboratory and numerical studies [*Cenedese and Whitehead*, 2000; *Zamudio et al.*, 2002]. These studies indicate that when a current flows around a cape, several conditions are necessary for the formation of an eddy and its subsequent detachment from the cape. These conditions include: an appropriate water depth, a steep slope (>0.25) and a strong boundary current. These conditions were met by our study region after these storms. These studies also indicate that storms making landfall either east (i.e., westward currents [see *Cenedese and Whitehead*, 2000]) or west [*Zamudio et al.*, 2002] of the cape are likely to generate anticyclonic eddies.

[14] Although the two storms reported here made landfall from as far east as western Florida and as far west as western Louisiana, they both generated eddies near the Mississippi River delta. In a climatology study, each Gulf coast state was divided into western, central, and eastern regions from Texas to Florida [*Muller and Stone*, 2001]. On average, each region is impacted by a tropical storm or hurricane every three years [*Muller and Stone*, 2001] and it is likely that most of these storms would result in eddies similar to those reported here. Therefore coastal eddies of this type will occur more frequently than every three years, perhaps as often as annually.

[15] The high concentrations of *chl a* in open ocean regions presented above result from the fertilization of seawater by fluvial nutrients and the consequent phytoplankton bloom. The river plume is characterized by high concentrations of dissolved nutrients, whereas gulf waters are permanently stratified and oligotrophic [*Turner and Rabalais*, 1994]. Reported phytoplankton carbon specific growth rates range from 0.8 to 2.3 d^{-1} in the river plume [*Redalje et al.*, 1992]. At these rates, the biomass would double every 0.87 to 0.3 days. Therefore the offshore ocean color features described here reflect in situ production rather than transported biomass. Consequently, these storm-induced injections of the river plume fertilize gulf water and stimulate biological production.

[16] Oceanic eddies (cyclonic in northern hemisphere) can enhance vertical mixing, pump up nutrients [*McGillicuddy et al.*, 1998], and lead to phytoplankton blooms in various marine waters [*Pegau et al.*, 2002; *Seki et al.*, 2001; *Signorini et al.*, 1999; *Subrahmanyam et al.*, 2002; *Toner et al.*, 2003]. Our data indicate that oceanic eddies can also entrain coastal waters thereby enhancing river-ocean interactions. While eddies presented here are anticyclonic and located to the west of the river mouth, cyclonic eddies located to the east of the river mouth could also inject plume water into the open gulf. The time scales of these suggest that fluvial impacts may be larger and extend further than previously thought. Furthermore, as hurricanes and tropical storms are not unique to the northern Gulf of Mexico, this process may also occur near other rivers.

[17] In general, events like these have been excluded or poorly represented in studies of riverine impacts on the oceans [*Liu et al.*, 2000]. Sea surface temperature (SST) has been used to study river-ocean interactions but was restricted to the winter seasons when there is a significant temperature difference between fresh water and seawater [*Walker et al.*, 1996; *Muller-Karger et al.*, 1991]. With advances in remote sensing of SSH and *chl a*, it is now practical to monitor and characterize the impact of major storms and include them in flux calculations.

[18] A systematic re-estimation of fluvial flux requires field studies of the injected plumes and is beyond the scope of the present paper. However, to demonstrate the potential effects of the process described here, we estimated the DOC flux after Tropical Storm Barry. DOC is transported to the coastal ocean by the Mississippi River and is also generated by biogeochemical processes in the river plume [*Guo et al.*, 1999]. Assuming the DOC concentration was 250 μM in the plume water [*Guo et al.*, 1999] and the depth of the mixed layer was 10 m [*Chen et al.*, 2000], the river plume, which was ~30 km wide (Figure 3) and traveling at ~ 0.5 m s^{-1} (Figure 2), might have transported $\sim 5.4 \times 10^{11}$ g DOC to the open Gulf of Mexico in two weeks. This is more than one fourth of the annual DOC flux of $\sim 2.1 \times 10^{12}$ g by the Mississippi River. We based this conclusion on an annual water discharge of 5.30×10^{11} $m^3 yr^{-1}$ [*Milliman and Meade*, 1983], and freshwater DOC concentration of 330 μM [*Guo et al.*, 1999]. *Liu et al.* [2000] noted that fluxes of carbon to the continental margin could not be balanced by sedimentation and observed offshore export processes, and speculated that the field observations may have missed important export mechanisms. The process presented here may be one of them.

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