Response of sea surface properties to Hurricane Dennis in the eastern Gulf of Mexico

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1 Sea Surface Reflectance (SSR) and Sea Surface Temperature (SST) were assessed in the eastern Gulf of Mexico in early July 2005 after passage of Hurricane Dennis, a category 4 storm, using data from the MODIS, SeaWiFS, and AVHRR satellite sensors, historical hydrographic and nutrient surveys, and a simple vertical water column mixing model. The bathymetric gradient across the shelf break, the offshore deep nutricline, and nearby Loop Current eddies led to unique SSR and SST changes after the passage of Dennis. In waters shallower than 50 m, a strong sediment resuspension event led to higher SSR in the visible and an increase in the MODIS fluorescence line height (FLH). These variables returned to pre-storm conditions after about 10 days. The FLH change indicates increasing biomass in the short response time (<2 days), which might have been due to resuspended benthic and/or near-bottom algae, as opposed to simply new primary production in the overlying water column. The SST changes occurred almost entirely along the right side of the hurricane track (1.96 ± 0.66°C for an area of 158,600 km2). Waters >50 m deep cooled down significantly, but there was no apparent change in SSR, presumably because the nutricline was too deep to be affected by vertical mixing due to the storm. The three-dimensional hydrographic and nutrient structure in waters near the west Florida shelf defines what changes may be detected at the surface with remote sensing. Citation: Hu, C., and F. E. Muller-Karger (2007), Response of sea surface properties to Hurricane Dennis in the eastern Gulf of Mexico, Geophys. Res. Lett., 34, L07606, doi:10.1029/2006GL028935.

1. Introduction

Dramatic surface cooling and color changes in the ocean have been documented after the passage of a hurricane [Stramma et al., 1986; Shay et al., 1992; Hoge and Lyon, 2002; Lin et al., 2003; Babin et al., 2004; Davis and Yan, 2004; Walker et al., 2005]. Changes in sea surface reflectance (SSR) may be due to increased surface primary productivity resulting from nutrients supplied by deep mixing or upwelling [Babin et al., 2004] and/or entrainment of the deep chlorophyll maxima [Walker et al., 2005]. Some investigators have proposed that SSR changes are more likely due to enhanced colored dissolved organic matter (CDOM) [Hoge and Lyon, 2002]. In the coastal ocean, hurricanes can also cause sediment resuspension/transport as well as coastal erosion and flooding [e.g., Yuan et al., 2004].

In early July 2005, Hurricane Dennis (a category 4 storm) swept across the eastern Gulf of Mexico (EGOM) and the west Florida shelf (WFS). Sediment resuspension, surface cooling, and other unique features were observed in satellite-derived SSR and SST images: (1) a contrast in SST response on either side of the 30-m isobath; (2) a large increase in the solar stimulated fluorescence over the shallow portions (<50 m) of the shelf; and (3) negligible changes in SSR over deeper shelf waters, where surface cooling was maximum.

The upper ocean heat and temperature response to Hurricane Dennis has been modeled by Morey et al. [2006], yet the unusual physical and biological features have not been documented or explained. Here we report on these unique changes and use concurrent satellite data, historical field surveys, and a simple mixing model to explain the underlying driving mechanisms. We hypothesize that hurricane perturbation over shallow waters can yield information on the summertime thermocline and nutricline depth as well as on the role of bottom-dwelling algae.

2. Data Sources

SST data were obtained from the Advanced Very High Resolution Radiometer (AVHRR on NOAA Polar Orbiters 12, 15, and 17) and from the Moderate-resolution Imaging Spectroradiometer (MODIS on the Terra and Aqua satellites). SSR and related products (chlorophyll-a concentration or Chl, fluorescence line height or FLH) were obtained from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and MODIS. AVHRR data were processed using the TerraScan software from SeaSpace, and SeaWiFS and MODIS data were processed using NASA software SDA4.8.

Historical CTD and nutrient data in the EGOM were obtained from the Northeastern Gulf of Mexico (NEGOM) program (1998–2000), the EcoHAB program (1998–2001), and a field survey conducted to the Florida Current in August 2004 [Hu et al., 2005a]. Data for Hurricane Dennis, including the storm category, eye location, maximum sustained wind speeds, and hurricane force wind radii were obtained from the National Hurricane Center, U.S.A.

3. Results

Figure 1 shows the surface cooling that occurred to the right of the hurricane track. The average cooling in the core of the cold plume (area outlined in Figure 1b) was –1.96 ± 0.66°C (minimum was –9.4°C). In total, an area of ~158,600 km² was defined by the difference between SST on July 11 (26.47 ± 0.58°C) and the 1-week average SST prior to the passage of Dennis (28.43 ± 0.37°C). Over shelf
waters <30 m deep, between Cape San Blas and Dry Tortugas (an area ~36,000 km²), the SST response was smaller (−1.66 ± 0.60°C, from 29.23 ± 0.44 to 27.57 ± 0.59). Before Dennis, these shallower waters were ~0.8°C warmer than deeper waters toward the shelf break. This likely was in part the cause of the SST gradient across the 30-m isobath after Dennis (Figure 1b). The significant sediment resuspension event over the entire <50 m shelf (Figure 2b) suggests that the water column was well mixed by the storm, but that there was no cooler water near the <30 m bottom to help cool the surface.

Along with the resuspended sediments, we observed a significant enhancement of the MODIS FLH signal (Figure 2d). Except for a small filament near the edge of a Loop Current eddy around 26°N, 84–86°W (Figure 2d), there was no detectable change in FLH or SeaWiFS Chl in waters >50 m depth, even in the area of pronounced surface cooling. Further, there was no significant change in either \( R_{rs}(443) \) or \( R_{rs}(555) \) (Figure 3a). Clearly, for deep waters (> 50 m), bio-optical and biological responses are minimal. This is in contrast to previous reports suggesting that hurricanes at these latitudes stimulate phytoplankton blooms in their wakes.

4. Discussion

4.1. Forcing

How much force is needed to cause the unusual SST and ocean color response in the wake of Dennis? The cyclonic wind associated with a hurricane will result in deep mixing and upwelling, particularly on the right side of a hurricane’s track. If the water is already well mixed down to the bottom prior to the passage of the storm, SST changes should be small. Data collected in the past in the EGOM around the same time of the year (Figure 4) suggest that the surface layer due to summer stratification is about 20–30 m, at least over most of the shelf and out to the 1000 m isobath. If mixing were to occur to greater depths, reaching cooler water, a change in SST may be expected.

The downward isopycnal displacement of the seasonal thermocline in waters deeper than 30 m can be approximated as \[ \eta = \tau/\left(\rho_w U_h\right) \] where \( \tau \) is the wind stress derived as a function of wind speed (\( U_{10} \), m s\(^{-1}\)) and air density (\( \rho_a = 1.26 \text{ kg m}^{-3} \)) and \( f \) is the Coriolis parameter, and \( U_h \) (m s\(^{-1}\)) is the hurricane transition speed.

The maximum sustained wind speed (MSW) was 56.1 ± 7.9 m s\(^{-1}\) during Dennis’ passage, and the corresponding isopycnal displacement was estimated as 38.3 ± 19.3 m. The associated average surface cooling, estimated as the difference between the average temperature for the water depth of 30 + 38.3 m and the pre-hurricane

Figure 1. Sea surface temperature (SST, °C) (a) before and (b) after Hurricane Dennis. (c) SST changes. The weekly mean SST in Figure 1a shows dominant current directions associated with Loop Current and LC eddies (outlined in dashed blue lines with arrows, as obtained from visual interpretation and confirmed by sea surface height imagery). The overlaid numbers indicate the location of the hurricane eye and the category, at approximately 2-hour steps, starting from the south around 9 July 2005, 05:00 GMT. Overlaid green lines show bathymetry contours for 30, 40, 50, 100, 200, 500, and 1000 m. In Figure 1b, the maximum surface cooling is outlined by the black dashed line, and the outline is overlaid in Figure 1a to show its relationship with the pre-hurricane LC and eddies. An area of about 20,000 km² between 100- and 500-m in the center of the cooling (blue outline in Figure 1b) was chosen to study the changes in several bio-optical properties. The color scales used to code the SST in the images were adopted from a fixed omni-scale to cover the entire SST range (0–31°C) to assist time-series analysis for the global ocean. In Figure 1c, the U-shaped maximum cooling (dark blue) is due to the relatively low SST near the 100-m and 200-m isobaths between 26°N and 28°N during 2–8 July 2005 (Figure 1a).
The actual wind speed changes as a function of distance from the eye [e.g., Weisberg and Zheng, 2006]. A land-based station near Tampa Bay recorded MSW of about 20 m s\(^{-1}\). It is therefore assumed that wind was between 30 – 60 m s\(^{-1}\) for the cooling area, most of which should experience <2.8\(^\circ\)C cooling due to isopycnal displacement alone. Considering the size of the cooling area (158,600 km\(^2\)) and factors such as heat loss, inhomogeneous vertical mixing, which we do not estimate but which also affect SST, this result (<2.8\(^\circ\)C) agrees reasonably well with that observed from the satellites.

**Figure 2.** MODIS imagery showing changes in (a, b) SSR and (c, d) FLH from before to after Dennis, where the entire <50-m shallow shelf experienced significant sediment resuspension and increase in FLH. Elevated FLH values were also found near an LC eddy edge, as annotated with the black arrows in Figure 2d.

30 m (Figure 4), is 26.9 – 29.7 = 2.8°C. The actual wind speed changes as a function of distance from the eye [e.g., Weisberg and Zheng, 2006]. A land-based station near Tampa Bay recorded MSW of about 20 m s\(^{-1}\). It is therefore assumed that wind was between 30 – 60 m s\(^{-1}\) for the cooling area, most of which should experience <2.8°C cooling due to isopycnal displacement alone. Considering the size of the cooling area (158,600 km\(^2\)) and factors such as heat loss, inhomogeneous vertical mixing, which we do not estimate but which also affect SST, this result (<2.8°C) agrees reasonably well with that observed from the satellites.

**Figure 3.** SST and SSR parameters before and after Hurricane Dennis in the EGOM. (a) For the area between 100- and 500-m isobath and between 26.5 and 28.5\(^\circ\)N (outlined in blue in Figure 1b). (b) For the entire shallow (<50 m) shelf region from Cape San Blas to Dry Tortugas. The dashed lines denote the one-week mean values before hurricane Dennis. SSR parameters were derived from SeaWiFS from the dates when at least half of all pixels in the area were valid.

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**4.2. Perspective**

Walker et al. [2005] observed average surface cooling of about −1.9°C on both sides of a hurricane track in the NGOM near the Mississippi Delta, and a filament of enhanced SeaWiFS Chl only 1.5 days after the hurricane passage (from 0.36 to 0.50 mg m\(^{-3}\)). Two days later, the Chl in the patch reached a maximum concentration of 0.81 mg m\(^{-3}\). Similarly, Davis and Yan [2004] observed Chl-rich coastal filaments after a hurricane’s passage using SeaWiFS data. More generally, Chl enhancement in the wake of a hurricane in the open ocean was reported by Babin et al. [2004]. However, Hoge and Lyon [2002] concluded that the color change in the open ocean was
Funding was provided by the US National Science Foundation (NSF) and the US National Aeronautics and Space Administration. Douglas Biggs and Leila Belabbassi (Texas A&M Univ.) provided historical hydrographic and nutrient data on the Loop Current and other deep Gulf waters. These data were used to understand the hydrographic properties in the EGOM. Over deeper waters, most of the waters to the left of the hurricane track were in the Loop Current and other deep Gulf waters. These responses are different from those reported by previous studies of SST and chlorophyll concentration, 2006) were resuspended, leading to the increased FLH signal after Dennis. Field sampling in future research needs to focus on benthic properties of the shallow shelf to confirm or reject this hypothesis.

The sediment resuspension was largely restricted to the <50 m shelf, and occurred during the maximum sustained wind speed of 56 ± 7.9 m s⁻¹. Similar observations were made during three hurricanes that affected the WFS during summer 2004 (Charley, Frances, and Jeanne), when sediment resuspension events were always restricted to waters <50 m deep.

Why did the surface cooling occur almost entirely to the right side of the track of Dennis (Figure 1b)? In the past, much emphasis has been placed on the asymmetric distribution of wind and physical forcing around the periphery of these storms. However, there is also spatial heterogeneity in the hydrographic properties in the EGOM. Over deeper waters, most of the waters to the left of the hurricane track are in the Loop Current and other deep Gulf waters (Figure 1a). Historical data (e.g., Figure 4 (bottom), profile labeled FC) shows that the water in the Florida Current (an extension of Loop Current) is warmer below 30 m than waters outside the current at the same depth, and that the thermocline is at least 60 m deep. Therefore it is more difficult to mix to depths that will lead to surface cooling. The shape of the area that experienced cooling was outlined as a black line in Figures 1a and 1b. These patterns are clearly of interest in defining the heat content of surface waters that can provide heat to sustain storm strength.

5. Conclusion

Unusual patterns of surface cooling and SSR changes occurred after passage of Hurricane Dennis in the eastern Gulf of Mexico in early July 2005. These include surface cooling to the right of the hurricane track in shelf waters >30 m, but more limited cooling in shelf waters <30 m. Significant sediment resuspension over the <50 m shelf was accompanied with a strong increase in MODIS fluorescence line height signals. These changes are different from those reported by previous studies of SST and chlorophyll changes in the wake of a hurricane. The differences can be explained by the three-dimensional hydrographic and nutrient structure in waters near the west Florida shelf.

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References

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