Bottom scour observed under Hurricane Ivan

William J. Teague,[1] Ewa Jarosz,[1] Timothy R. Keen,[1] David W. Wang,[1] and Mark S. Hulbert[1]

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[1] Observations that extensive bottom scour along the outer continental shelf under Hurricane Ivan resulted in the displacement of more than 100 million cubic meters of sediment from a 35 × 15 km region directly under the storm's path are presented. Sediment resuspension was accomplished by the extreme waves generated by Ivan and transported by strong near-bottom wind-driven currents. The sediment transport was primarily westward along the shelf, but also contained a significant offshore component, suggesting sediment was transported toward the Mississippi Delta and that it may have accumulated near the shelf break and on the upper continental slope. The maximum observed scour of about 32 and 36 cm took place at two locations approximately 17 km apart along the 60 m isobath over which the maximum wind stress occurred.
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1. Introduction

[2] Maximum wind stress and wave heights generated by Hurricane Ivan occurred over six moorings containing acoustic Doppler current profilers (ADCPs) and wave/tide gauges deployed by the Naval Research Laboratory on the outer continental shelf in the northeastern Gulf of Mexico at depths of 60 and 90 m (Figure 1) [*Wang et al.*, 2005; *Mitchell et al.*, 2005]. The combination of water pressure, surface wave, and near-bottom current data allow bottom scour to be evaluated.

[3] Continuous water pressure measurements (see Supporting Methods in the auxiliary material[1]) reveal the mean depth of all six moorings increased after the passage of Hurricane Ivan. Video monitoring during remotely operated vehicle (ROV) recovery of the two moorings with the greatest depth change showed they were resting normally on the bottom, were not covered by sediment, and showed no signs of localized scour (i.e., the moorings were not sitting in small-scale depressions). These moorings required ROV recovery because their interior spaces were filled completely with sediment (mostly sand) (Figure 2) and did not release properly during recovery. Internal attitude sensors (pitch/roll) in the ADCPs remained steady prior to and after the passage of Ivan, but fluctuated several degrees during Ivan's passage (see Supporting Methods). These factors indicate that scour occurred on the outer continental shelf under Hurricane Ivan.

[1]Naval Research Laboratory, Stennis Space Center, Mississippi, USA.

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2. Bottom Scour

[4] Bottom scour results from a combination of wave-driven sediment resuspension and current-driven transport of the resuspended sediment [*Keen and Glenn*, 2002]. Hurricane Ivan produced the largest wave field ever measured under a hurricane with maximum and significant wave heights about 28 m and 18 m, respectively, near the locations under maximum wind stress [*Wang et al.*, 2005]. Near-bottom orbital wave velocities (>2 m s^{-1}) calculated using linear wave theory [*Dean and Dalrymple*, 1991] over a suite of measured wave amplitudes and periods suggest the wave field was sufficient to generate sediment resuspension at all six moorings, but particularly at moorings 2 and 3 which were directly under the maximum wave field at 60 m depth. Near-bottom currents ranged from 0.40 to 1.20 m s^{-1} at all six moorings during Hurricane Ivan's passage [*Mitchell et al.*, 2005] while scour occurred. Thus, the currents were sufficient to transport the resuspended sediment and generate scour.

[5] Sediment resuspension was greatest in the region where maximum wind stress occurred, and it led to about 32 cm and 36 cm of scour at moorings 2 and 3 which were 17 km apart along the 60 m isobath (Figure 1). The other four moorings had about 8 cm of scour mainly due to greater depths and/or locations west of the maximum wave heights and wave-induced currents. Assuming the amount of scour varied linearly between the 6 mooring sites, approximately 100 million cubic meters of sediment (mostly sand [*Sawyer et al.*, 2001]) were scoured and transported to the southwest from a 35 km × 15 km region spanned by the moorings.

[6] A progressive vector diagram (pvd) of near-bottom currents (Figure 3), which provides an estimate of Lagrangian motion from Eulerian measurements, shows a net sediment transport to the southwest while sediment was being resuspended by wave action. The majority of observed scour occurred along a 17 km region at 60 m depth, and the pvd suggests the sediment was transported toward the Mississippi Delta and redeposited on the shelf and/or near the shelf break. British Petroleum (BP) reported [*Thompson et al.*, 2005] a 44 km segment of pipeline located 40 km west of our mooring array at about 65 m depth was displaced toward the shelf break approximately 600 m before contact with a platform halted its down slope migration. They suggested the pipeline was moved by bottom currents carrying entrained sediments which increased the water density and mass, thus giving it the strength to move the unanchored pipeline. These facts additionally support our conclusions that the wave action and currents under

[1]Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2005gl025281.

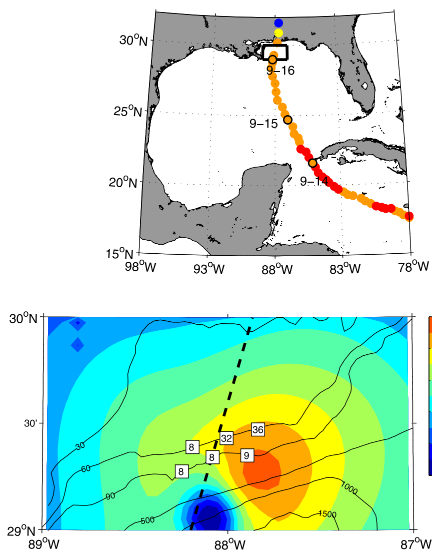

Figure 1. (top) Path of Hurricane Ivan through the Gulf of Mexico. Color signifies intensity (blue = 1, yellow = 3, orange = 4, red = 5). The open black circles show the location of the eye at 0000 UTC on September 14, 15, and 16. The black box signifies the region displayed below. (bottom) Bathymetry, path of Hurricane Ivan's eye, wind stress, and instrument locations south of Mobile Bay, Alabama. Moorings 1, 2, and 3 are from left to right at 60 m depth and Moorings 4, 5, and 6 are from left to right at 90 m depth. The numbers contained in the boxes are the amount of scour seen at each mooring in centimeters. The black contour lines are the depth in meters. The colored contours are the wind stress in Pascals.

Hurricane Ivan were sufficient to resuspend and transport sediment over a region at least 80 km wide, or equal to twice Hurricane Ivan's radius of maximum winds, and the transport had an offshore component throughout that region. The orientation of the Gulf Coast, the typical path traveled by a tropical cyclone impacting the Gulf Coast, and the cyclonic circulation generated by tropical cyclones, dictates that a strong westward flow always develops over the continental shelf under the northern half of hurricanes. Thus, repeated tropical cyclone passages over time may result in a net migration of sediment from the region of these measurements toward the Mississippi Delta.

[7] In addition to the sediment resuspension, wind generated surface waves apply cyclic pressure to bottom sediments causing seabed motion. Unconsolidated sediments tend to move upward under the trough, downward under the crest, and move laterally under the waves inflection points. Important sediment engineering properties, such as the shear modulus, shear strength, and viscosity, which partly control the magnitude of sediment motions are known to degrade during the passage of a storm due to wave action [*Hooper and Suhayda*, 2005]. When these properties degrade, the magnitude of sediment motion increases and the shear strain increases.

[8] Surface wave-induced seabed motion is common in the single-frequency range of .05–.5 Hz (periods of 2–20 s), and is several orders of magnitude greater than the motion induced by seismic energy in the double-frequency band [*Trevorrow et al.*, 1989]. A typical displacement caused by pressure variations under surface waves for the coastal seabed is on the order of 0.1 mm. The surface wave-induced seabed motion can be modeled using a combination of linear water-wave theory and elastic seabed theory. This theory indicates that the vertical displacement in a homogeneous, elastic seabed is a linear function of the wave amplitude [*Yamamoto et al.*, 1978]. Seabed displacements of 1 cm have been measured during a winter storm in the Gulf of Mexico with 3 m waves [*Forristall and Reece*, 1985]. Thus, it is reasonable to extrapolate that Ivan with an 18 m significant wave height would cause approximately 6 cm of displacement. A model of the generation of microseismic energy from surface waves suggests that this

Figure 2. Photograph of the interior of a mooring showing the sand that had completely filled the interior spaces of the instrument. The yellow instrument is an acoustic release. The hand belongs to Andrew Quaid, a marine technician.

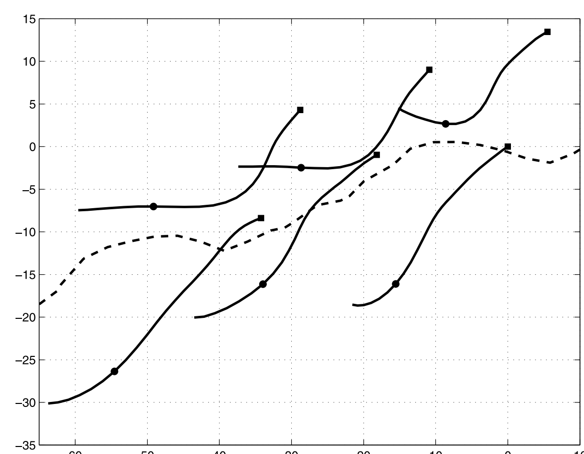

Figure 3. Progressive vector diagram over a 12 hour period after scour began, showing the direction and distance sediment likely traveled. The dashed line represents the location of the shelf break. The solid black square represents the mooring locations and the beginning of active scour, and the solid circle marks the time when active scouring likely ceased. Axes labels are km.

energy is significant to depths of 70 m below the seabed [*Okeke and Asor*, 2000].

3. Summary

[9] Significant bottom scour occurred under Hurricane Ivan as it passed over the outer north eastern shelf in the Gulf of Mexico. The scour occurred through a combination of near-bottom wave orbital velocities which generated sediment resuspension, and strong near-bottom wind driven currents which transported the resuspended sediment away. The maximum observed scour of approximately 32 and 36 cm occurred along the 60 m isobath over which the maximum wind stress occurred. The large surface waves under Hurricane Ivan, in addition to scouring unconsolidated sediments, may also have applied significant stress to underlying sediments to a depth of 60 m, possibly generating up to 6 cm of cyclic displacement within them. This suggests that major hurricanes passing over the Continental Shelf anywhere in the northern Gulf of Mexico may significantly alter the seafloor directly under their paths.

[10] In addition to these seafloor modifications, hurricanes in this part of in the Gulf of Mexico may also cause an accumulation of large quantities of sediment along the shelf edge near the Mississippi Delta. This enhanced accumulation could have far reaching consequences. Deep growth faults extending 500 m deep into the sediment are known to exist near the edge of the shelf off the modern Mississippi River delta [*Coleman and Prior*, 1988]. A major mass wasting event (or slump), known as the East Breaks Slump, occurred 5000 to 10,000 years ago off the Texas coast in the northwestern corner of the Gulf of Mexico in a highly faulted region containing deltaic deposits [*Trabant et al.*, 2001]. Sediment from a 3200 km^2 area slumped and moved 145 km down slope from the shelf edge to a depth of 1500 m. Based on the slump's overall dimensions, it was estimated that a 7.6 m tsunami would have been generated and slammed into the Texas coast. Failure of a fault off the South Pass of the Mississippi Delta in the recent geologic past led to a slump event that moved sediment from an approximately 8600 km^2 area 300 km downslope to a depth of 3000 m [*Walker and Massingill*, 1970]. The height of the ensuing tsunami was not estimated. However, the slump was about twice as large as the East Breaks Slump and may have generated a tsunami as large, or possibly larger. The mechanism initiating these two slumps is unknown, but they both occurred in faulted areas along the shelf break covered with loose, unconsolidated deltaic sediments on low angle slopes. Since major earthquakes are virtually unheard of in the Gulf of Mexico, our measurements suggest hurricanes may generate sufficient strain, due to sediment accumulation and intense cyclic wave-motions, to induce these large-scale slumping events that, in turn, could trigger a tsunami-like event in the Gulf of Mexico similar to the ones that occurred in the geologic past [*Trabant et al.*, 2001].

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References

Coleman, J. M., and D. B. Prior (1988), Mass wasting on continental margins, *Ann. Rev. Earth Planet. Sci.*, *16*, 101–119.

Dean, D. R., and R. A. Dalrymple (1991), *Water Wave Mechanics for Engineers and Scientists*, vol. 2, *Advanced Series on Ocean Engineering*, 368 pp., World Sci., Hackensack, N. J.

Forristall, G. Z., and A. M. Reece (1985), Measurements of wave attenuation due to a soft bottom: The SWAMP experiment, *J. Geophys. Res.*, *90*, 3367–3380.

Hooper, J. R., and J. N. Suhayda (2005), Hurricane Ivan as a geologic force: Mississippi Delta front seafloor failures, *Proc. Annu. Offshore Technol. Conf.*, pap. 17737.

Keen, T. R., and S. M. Glenn (2002), Predicting bed scour on the continental shelf during Hurricane Andrew, *J. Waterw. Port Coastal Ocean Eng.*, *128*, 249–257.

Mitchell, D. A., W. J. Teague, E. Jarosz, and D. W. Wang (2005), Observed currents over the outer continental shelf during Hurricane Ivan, *Geophys. Res. Lett.*, *32*, L11610, doi:10.1029/2005GL023014.

Okeke, E. O., and V. E. Asor (2000), On the microseisms associated with coastal sea waves, *Geophys. J. Int.*, *141*, 672–678.

Sawyer, W. B., C. Vaughan, D. Lavoie, Y. Furukawa, N. Carnaggio, J. Maclean, and E. Populis (2001), Northern Gulf Littoral Initiative (NGLI), geology and physical properties of marine sediments in the N. E. Gulf of Mexico: Data report, NRL/MR-MM/7430-01-8548, Naval Research Laboratory, Stennis Space Center, Miss.

Thompson, J., M. Garret, M. Taylor, T. George, M. Melancon, and K. Behrens (2005), Sonar surveys for pipeline inspection show extent of pipeline displacement and seafloor instability following Hurricane Ivan, *Proc. Annu. Offshore Technol. Conf.*, pap. 17738.

Trabant, P., F. L. Lettieri, and G. A. Jamieson (2001), East breaks slump, northwest Gulf of Mexico, *Proc. Annu. Offshore Technol. Conf.*, pap. 12960.

Trevorrow, M. V., T. Yamamoto, A. Turgut, and D. Goodman (1989), Measurements of ambient seabed seismic levels below 1.0 Hz on the shallow eastern U.S. continental shelf, *J. Acoust. Soc. Am.*, *86*, 2318–2327.

Walker, J. R., and J. V. Massingill (1970), Slump features on the Mississippi fan, northeastern Gulf of Mexico, *Geol. Soc. Am. Bull.*, *81*, 3101–3108.

Wang, D. W., D. A. Mitchell, W. J. Teague, E. Jarosz, and M. S. Hulbert (2005), Extreme waves under Hurricane Ivan, *Science*, *309*, 896.

Yamamoto, T., H. L. Koning, H. Sellmeijer, and E. van Hijum (1978), On the response of a poro-elastic bed to water waves, *J. Fluid Mech.*, *87*, 193–206.

M. S. Hulbert, E. Jarosz, T. R. Keen, W. J. Teague, and D. W. Wang, Naval Research Laboratory, Stennis Space Center, MS 39529–5004, USA. (teague@nrlssc.navy.mil)