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A detailed seabed signature from Hurricane Sandy revealed in bedforms and scour

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[1] On 30 October 2012, Hurricane Sandy made landfall near Brigantine New Jersey bringing widespread erosion and damage to the coastline. We have obtained a unique set of high-resolution before and after storm measurements of seabed morphology and *in situ* hydrodynamic conditions (waves and currents) capturing the impact of the storm at an inner continental shelf field site known as the "Redbird reef". Understanding the signature of this storm event is important for identifying the impacts of such events and for understanding the role that such events have in the transport of sediment and marine debris on the inner continental shelf. As part of an ONR-sponsored program designed to understand and characterize the ripple dynamics and scour processes in an energetic, heterogeneous inner-shelf setting, a series of high-resolution geoacoustic surveys were conducted before and after Hurricane Sandy. Our overall goal is to improve our understanding of bedform dynamics and spatio-temporal length scales and defect densities through the application of a recently developed fingerprint algorithm technique. Utilizing high-resolution swath sonar collected by an AUV and from surface vessel sonars, our study focuses both on bedforms in the vicinity of manmade seabed objects and dynamic natural ripples on the inner shelf in energetic coastal settings with application to critical military operations such as mine countermeasures.

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1. Introduction

[2] On 30 October 2012, Hurricane Sandy made landfall near Brigantine New Jersey bringing widespread erosion and damage to the coastline. We have obtained a unique set of high resolution before and after storm measurements of seabed morphology and in situ hydrodynamic conditions (waves and currents) capturing the impact of the storm at an inner continental shelf field site known as the "Redbird reef" [*Raineault et al*., 2013]. Understanding the signature of this storm event is important for identifying the impacts of such events and for understanding the role that such events have in the transport of sediment and marine debris on the inner continental shelf.

[3] As part of an Office of Naval Research (ONR)-sponsored program designed to understand and characterize the ripple dynamics and scour processes in an energetic, heterogeneous inner-shelf setting, a series of high-resolution geoacoustic surveys were conducted before and after Hurricane Sandy (Figure 1). Our overall goal is to

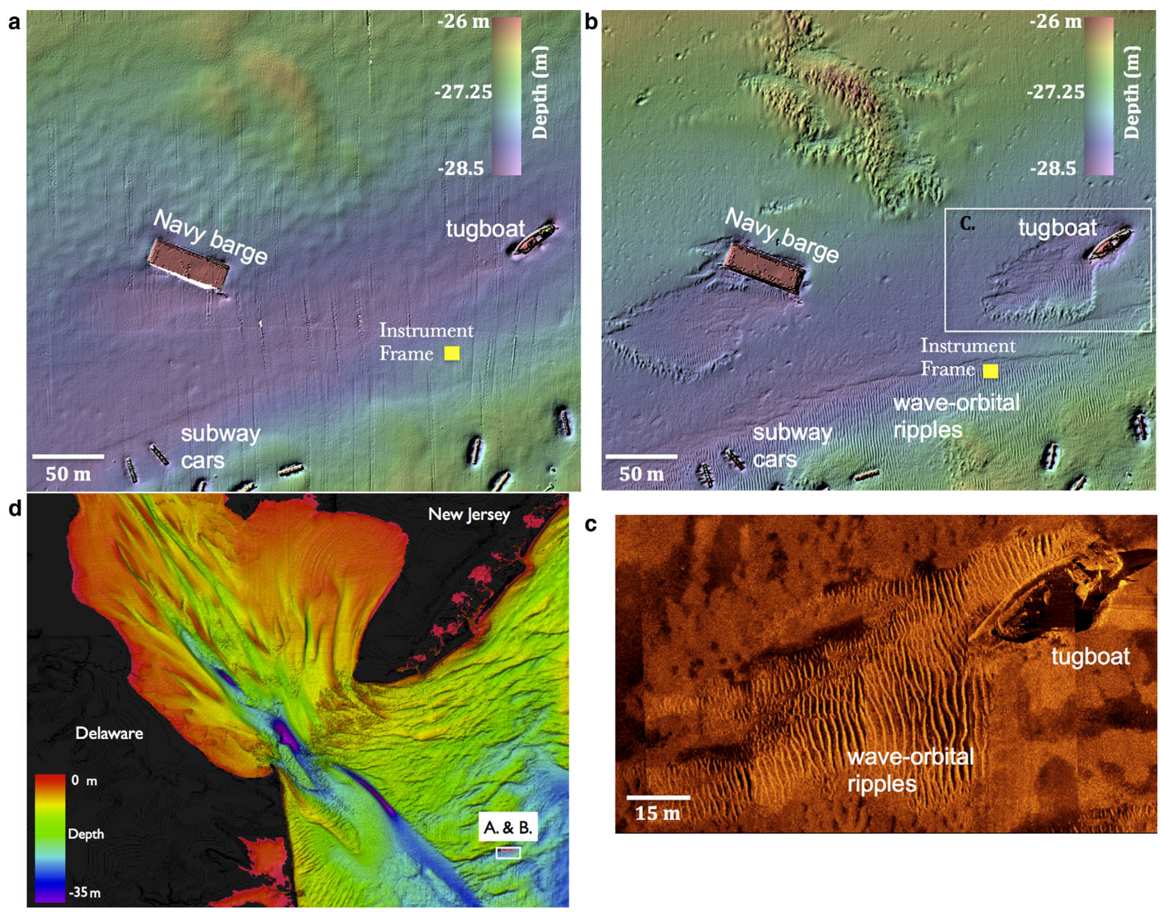


Figure 1. Multibeam echosounder, 25 cm sun-illuminated (azimuth 315° and 45° elevation) digital elevation model of the Redbird reef site (a) before Hurricane Sandy and (b) after Hurricane Sandy. Yellow box indicates location of seafloor instruments placed in the middle of a sorted bed form where large wave orbital ripples were generated by the storm. Figure 1b illustrates the pronounced bathymetric scour in the southwest lee of the Navy barge and tugboat produced in response to the storm conditions. (c) Close-up view of a submerged shipwreck showing large wave orbital ripples in the southwest lee of the structure created by storm waves mapped with AUV side-scan. Note that bright pixels in the side-scan sonar record equate to high amplitude of return and have been found from sediment samples (Figure 5d) to be generally associated with areas of coarse sand and gravel. Dark areas in the side-scan mosaic are associated with low amplitude of acoustic return and have been found from sediment samples and video to be associated with areas of fine sand and silt. (d) Overview color bathymetric image showing the location of the field site (white rectangle), data courtesy of NOAA Coastal Relief Model.

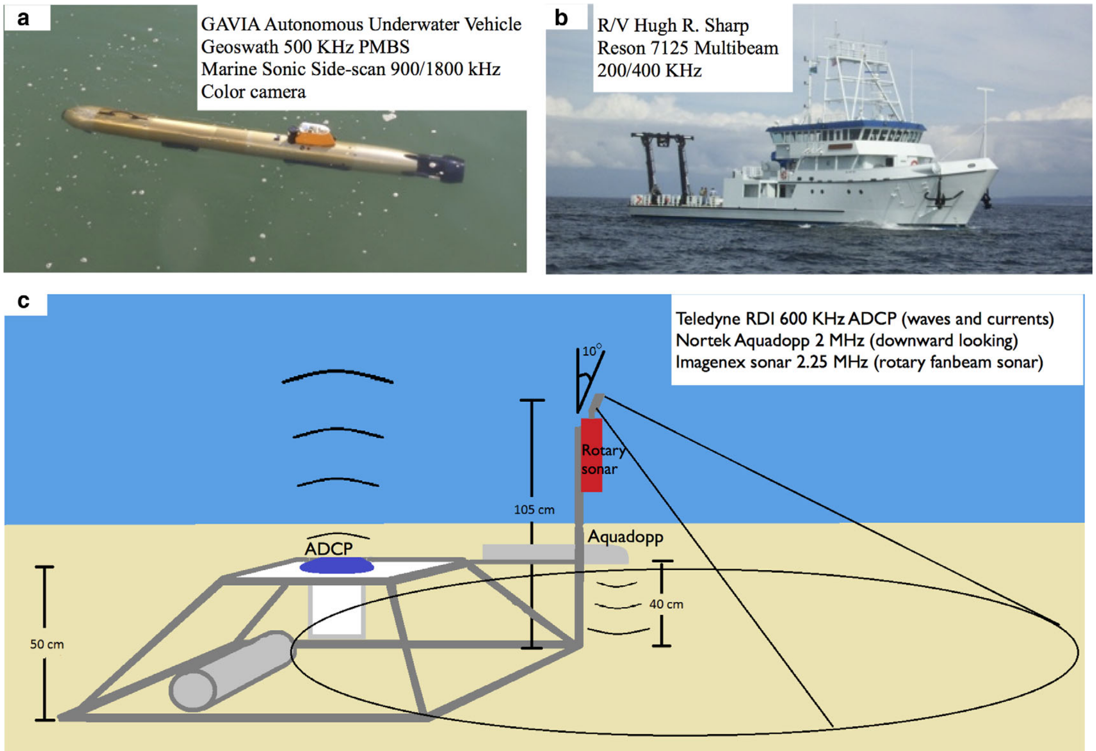


Figure 2. (a) Autonomous Underwater Vehicle (AUV) as outfitted for acoustic seabed mapping. (b) Surface vessel outfitted with dual frequency multibeam echosounder as configured for inner-shelf geoacoustic mapping. (c) Seabed instrument mooring used to gather *in situ* time series measurements of hydrodynamics of the water column including acoustic Doppler current profiler (ADCP) for measuring waves and currents, pulse-coherent Doppler profiler for measuring turbulence, waves, currents, and suspended sediment and rotary fanbeam sonar for obtaining planview side-scan images of the seabed.

improve our understanding of bedform dynamics and spatio-temporal length scales and defect densities through the application of a recently developed fingerprint algorithm technique [*Skarke and Trembanis*, 2011]. Utilizing high-resolution swath sonar collected by an AUV and from surface vessel sonars, our study focuses both on bedforms in the vicinity of manmade seabed objects and dynamic natural ripples on the inner shelf in energetic coastal settings with application to critical military operations such as mine countermeasures. Seafloor mapping surveys were conducted both with a ship-mounted multibeam echosounder and an Autonomous Underwater Vehicle (AUV) configured with high-resolution side-scan sonar (900 kHz) and a phase measuring bathymetric sonar (500 kHz) (Figures 2a and 2b). These geoacoustic surveys were further augmented with data collected by *in situ* instruments placed on the seabed that recorded measurements of waves and currents at the site before, during, and after the storm (Figure 2c).

2. Location and Methods

[4] Redbird Reef encompasses a 3.4 km^2 area approximately 29 km east of Indian River Inlet, Delaware at a mean depth of approximately 27 m (Figure 1). The artificial reef is composed of a series of ballasted tires, 997 former New York City subway cars and a combination of military vehicles, tugboats and barges emplaced between 1996 and 2009 [*Raineault et al*., 2013, 2011]. The reef site experiences both tidal current forcing [*Münchow et al*., 1992] and periodic storm events [*Raineault et al*., 2013], which, in combination with the artificial objects and sorted bedforms, makes the site ideally suited for a study of erosion processes on the inner continental shelf. Sorted bedforms are defined as adjacent heterogeneous patches of sediment alternating between fine sand in slight elevation (order 50–100 cm) next to depressions of coarse sand and gravel capable of supporting wave orbital ripples with wavelengths of 75–150 cm. For more background on and examples of sorted bedforms see *Trembanis et al.*

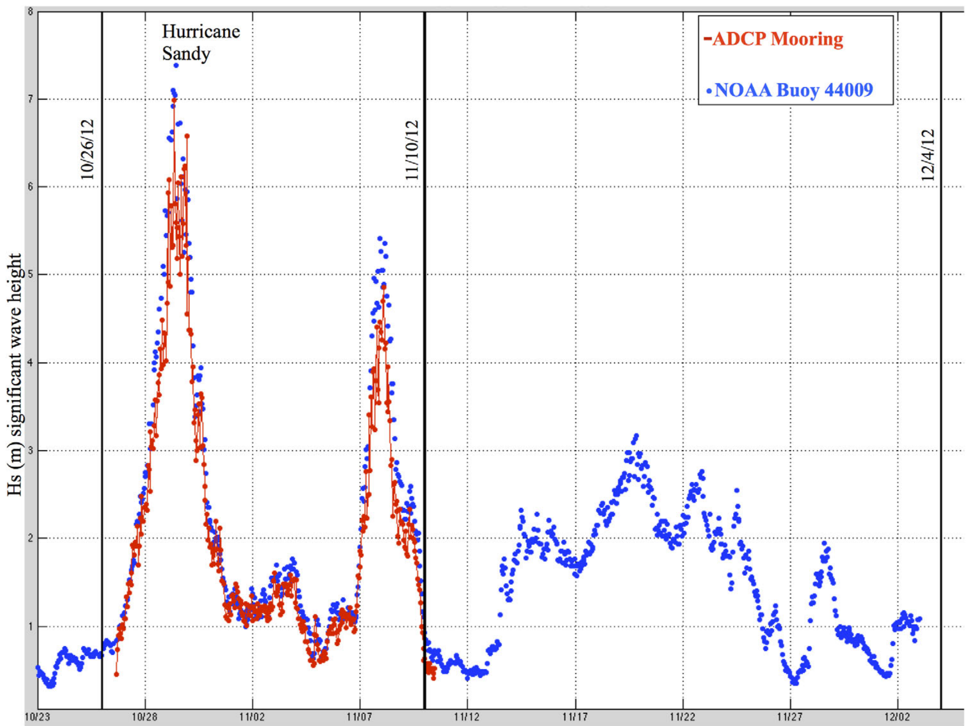


Figure 3. Time series of observed significant wave height as recorded by the in situ sensors (red line) and in comparison to the NOAA Buoy 44009 record (blue dots). Significant wave height is the average height of the highest one third of the waves in a sample in meters. NOAA Buoy 44009 is located approximately 11 nautical miles to the south of the field site in the same average water depth of 27 m. Vertical lines indicate the timing of ship multibeam and AUV surveys of the field site including 3 days before Hurricane Sandy and 12 and 36 days after the storm.

[2007], *Mayer et al*. [2007], *Murray and Thieler* [2004], and *Trembanis et al*. [2004, and references therein].

[5] The first of a series of geoacoustic surveys was conducted on 26 October 2012, 3 days ahead of the landfall of the storm and thus established a unique benchmark for determining the subsequent impact of the storm. A 1.0 × 0.5 km area (Figures 1a and 1b) was mapped using a Reson multibeam system (model 7125 SV2) deployed on RV Hugh R. Sharp (Figure 2b). The multibeam system was operated at 400 kHz for the greater resolution available in this configuration: the 1.0° × 0.5° beam width for transmit/receive allowed for spatial resolution on the order of 0.5 m × 0.25 m in water depths of 27 m for the near nadir beams. Raw Global Positioning System (GPS) measurements were recorded from an Applanix POSMV 330 (V5) and were postprocessed using Applanix POSPac MMS to reduce horizontal and vertical positioning uncertainties. By recording the GPS measurements, the data can be postprocessed to allow for improved accuracies based on knowledge of the satellite constellation orbits, clock corrections, atmospheric delays, etc. Vertical positioning provided by the POSMV allowed for an ellipsoidal reference, removing uncertainties associated with poor tidal knowledge offshore, heave sensor limitations and variations in draft/squat of the vessel between surveys. Vertical repeatability between surveys is on the order of 10–15 cm.

[6] Backscatter and bathymetry data from the multibeam were acquired at 200 kHz during a second pass over the site with the intent of using these data for acoustic seabed characterization. This approach was followed on every subsequent visit to the site, thus providing a time series of bathymetry and backscatter at both 200 and 400 kHz. Site surveys were conducted in this manner on the following dates: (1) 26 October 2012, 3 days before Hurricane Sandy, (2) 10 November 2012, 12 days after Hurricane Sandy, and (3) 4 December 2012, 36 days after the storm (Figure 3). The timing of each survey relative to the significant wave height conditions at the field site as recorded by the in situ ADCP mooring and the nearest NOAA wave buoy (Buoy 44009) are shown in Figures 3 and 4).

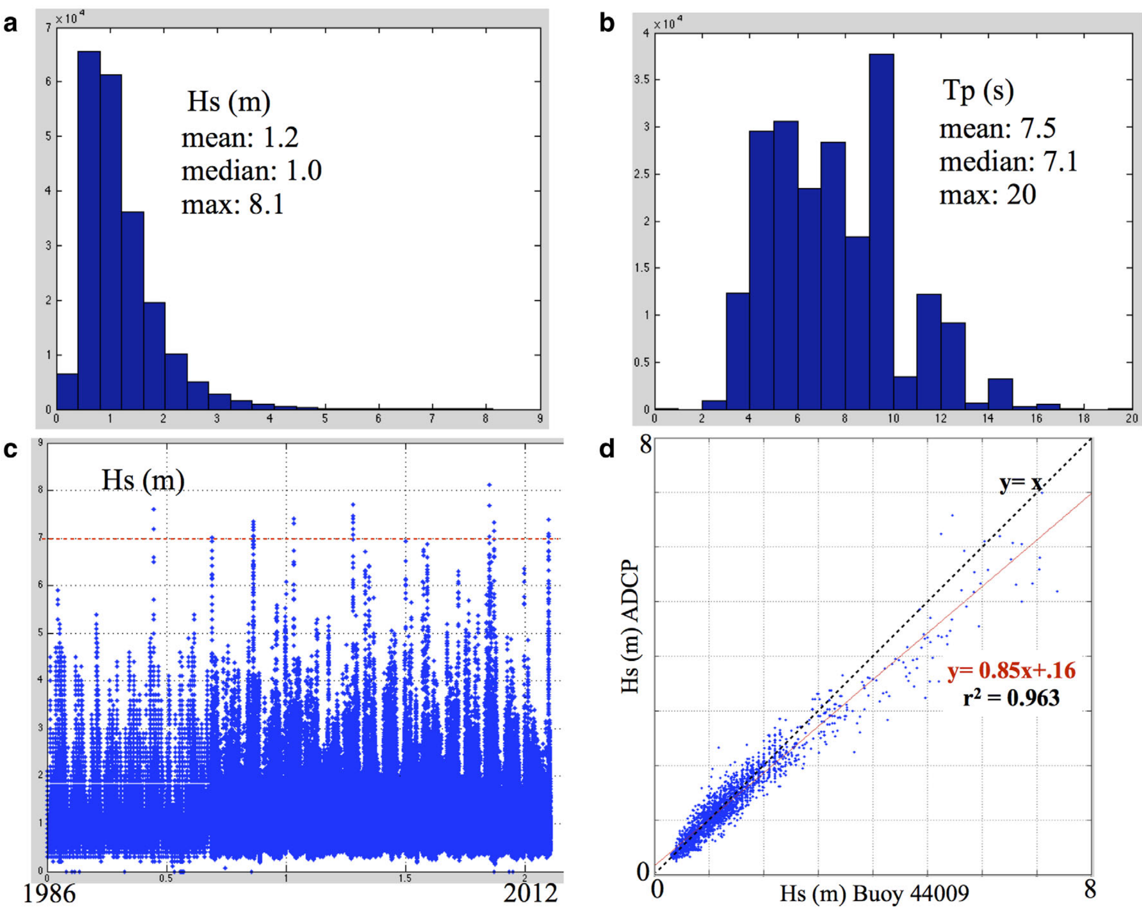
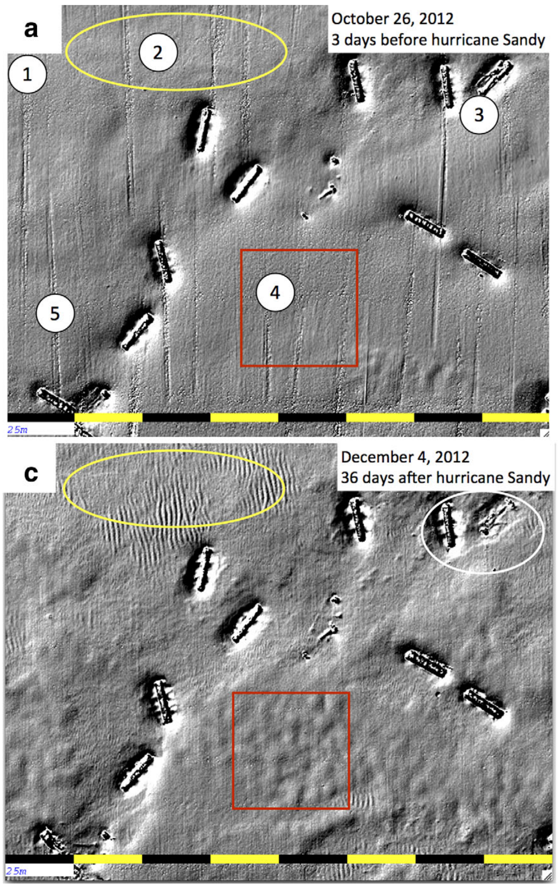


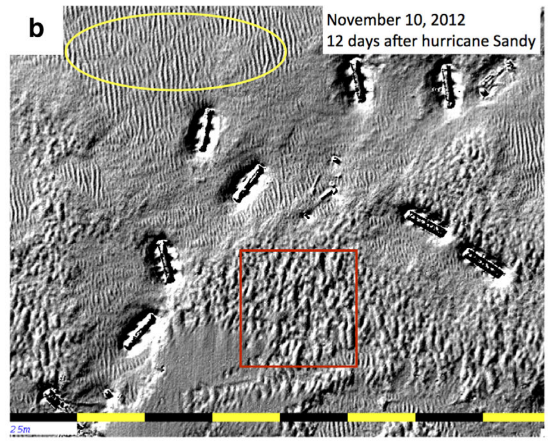
Figure 4. Wave climatology between 1986 and 2012 from NOAA buoy 44009 illustrating distribution of significant (a) wave height (Hs) and (b) peak wave period (Tp). (c) Time series of buoy observations illustrate 10 events with a significant wave height of more than 7 m for a recurrence interval of ~2.8 years for conditions of a magnitude similar to those created by Hurricane Sandy. (d) Cross plot of significant wave height conditions measured simultaneously by the in situ ADCP mooring (*y* axis) and buoy 44009 (*x* axis) showing a strong linear trend with a correlation coefficient (r^2) of 0.963.

Additional high-resolution side-scan sonar (900 kHz) and bathymetry (500 kHz) were collected using a Teledyne Gavia Autonomous Underwater Vehicle (AUV) (Figure 1c).

3. Storm Conditions

[7] Time series of waves (Figure 3), mean currents, and sonar data were recorded by an instrumented bottom mount frame comprised of an 600 kHz upward looking ADCP with wave and current profiling capability, a 2 MHz Aquadopp HR profiler for near-bed turbulence and 2.25 MHz Imagenex 881 rotary fanbeam sonar for time series measurements of bed form planview geometry (Figure 2c). The instrument assembly was situated (Figures 1a and 1b) within a large field (50–200 m wide and ~1000 m long) of moderately sorted gravelly sand with fines (Figure 5d). This seabed facies represents a sorted bedform feature consistent with the definition of sorted bedforms [*Raineault et al.*, 2013; *Murray and Thieler*, 2004; *Trembanis et al.*, 2004] in the vicinity of the Redbird reef structures [*Raineault et al.*, 2013]. Storm conditions were recorded at the surface and at the seabed before, during, and after Hurricane Sandy (Figure 3). Significant wave heights from Sandy reached over 7 m (Figure 3), with wave periods of 14 s. Significant wave orbital velocities were observed with speeds of over 1.5 m/s near the bed and mean currents during the storm were more than 0.6 m/s near the bed, tidal currents at the field site are typically less than 0.3 m/s in magnitude [*Raineault et al.*, 2013; *Münchow et al.*, 1992]. Within a week following Hurricane Sandy a nor'easter event brought additional storm conditions to the site (Figure 3). NOAA buoy 44009 data (located 18 km to the south at the same water depth as the field site)





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Sample #	Median grain size (mm)	%Gravel/ Sand/Silt	Description
1	0.32	0/99/1	well sorted medium sand
2	0.36	18/70/12	moderately sorted gravelly sand with fines
3	0.29	0/99/1	well sorted medium sand
4	N/A	0/99/1	well sorted medium sand
5	0.41	1/98/1	well sorted medium sand

Figure 5. The 25 cm/pixel gridded shaded relief bathymetric map close-up of a portion of the Redbird reef field site showing the same view and clutch of subway cars. (a) The first survey was conducted on 26 October 2012, 3 days before the impact of Hurricane Sandy on the field site and exhibits a generally undisturbed seabed of fine sand supporting smooth hummocky beds (red square). (b) The second survey was conducted on 10 November 2012, 12 days after the passage of Hurricane Sandy and shows the same view as in Figure 5a but with a dramatically different configuration of the seabed morphology. Large symmetrical wave orbital ripples are clearly evident in an area composed of moderately sorted gravelly sand with fines (yellow oval and sample 2 in Figure 5d). Additionally, scour pits have become more pronounced and expanded around the scattered subway cars and fluted scour jet marks are evident adjacent to the doors and window openings on the subway cars. Furthermore, areas that supported smooth well-sorted medium sand beds before the storm (red square in Figure 5a) have experienced significant scour and erosion into a jagged mottled topography (red square in Figure 5b). (c) The third survey was conducted on 4 December 2012, 36 days after the passage of Hurricane Sandy and illustrates partially (but not complete) recovery of the seabed to the pre-Sandy configuration. Note that in the red square in Figure 5c the previously jagged relief has been reduced to a partially smooth hummocky morphology. Additionally, some of the large wave orbital ripples have been smoothed out (yellow oval in Figure 5c) while some of the very same ripples mapped after hurricane Sandy are still present. The 45 sediment grab samples have been obtained at the field site and analyzed for grain size distribution including five samples (Figure 5d) taken within the area illustrated in Figures 5a–5c. These samples provide for a direct ground truth reference to the acoustic maps of bathymetry (Figures 1a and 1b) and backscatter (Figure 1c) conditions at the field site.

and on site ADCP wave height observations (Figure 3), exhibited strong correlation during both high energy and low energy conditions (Figure 4d). The buoy data and on site measurements exhibit a linear correlation coefficient (r^2) of 0.963 (Figure 4d) and therefore the long-term buoy data record provides a useful indicator of the wave climate conditions at this field site (Figure 4).

4. Findings

[8] Great care was taken to conduct both the before and after surveys utilizing the same sonar settings, line spacing, beam spacing, ping rates, and vessel speeds. Thus, the postprocessing settings and workflow were identical for both surveys and the resulting observed changes to the seafloor

(Figures 5a–5c) are real seabed feature changes and not the byproduct of some changes in survey design or gridding parameters. Pronounced features from the impact of Hurricane Sandy are strikingly evident in the comparison of the before and after multibeam data (Figures 1a, 1b, and 5a–5c). Large scour patches were noted in the southwest lee of seabed structures (Figures 1b and 1c). Also, previously smooth and/or hummocky patches of the seafloor (Figure 5a) became scoured and/or formed into large wave orbital ripples (Figure 5b) depending on the sediment texture of the surface sediment (Figure 5d). Symmetrical wave orbital ripples were clearly observed to have formed in response to the high-energy waves of the storm conditions with wavelengths of 1–1.5 m (Figure 5b). Within 36 days after the impact of Hurricane Sandy at the field site, hummocks had returned to some of the previously scoured areas and wave ripples formed by the storm, showed signs of having been partially buried or flattened by diffusion and bioturbation processes (Figure 5c). Perhaps most strikingly, several subway cars were rotated, further buried, or partially destroyed by the storm conditions with marine debris subsequently scattered throughout the area (Figure 5). Because only partial recovery was seen in December, 5 weeks later, there was likely little recovery in the short period (7 days) between Hurricane Sandy and the unnamed nor'easter storm, therefore we infer that it is reasonable to attribute the mapped morphological effects on the seabed to Hurricane Sandy.

[9] The freshly formed and exposed ripple fields observed in the mapping survey provide a unique high-resolution spatial snapshot of bedform morphology imposed by the storm conditions and form the basis of a continued effort to monitor the subsequent recovery of the seabed which is part of an ongoing investigation. These detailed repeated high-resolution mapping efforts and *in situ* hydrodynamic observations provide direct insights and confirmation of processes at the site that were previously [*Raineault et al*., 2013, 2011] only qualitatively inferred. While changes to the seabed following storm events are to be expected it is unique for scientists to have such carefully controlled and repeated surveys capturing the fine morphological details of a storm event over a large area. Often there are only cursory qualitative before and after maps of seabed morphology or spatially limited time series in one small footprint around a mooring, with far less resolution than presented here. These detailed repeated surveys allow researchers to examine the temporal evolution of scour dynamics for both natural bedforms (ripples) and manmade objects. There is an established body of literature highlighting the importance of understanding seabed scour with respect to both applied topics of the impacts of scour on manmade objects and shipwrecks [*Whitehouse*, 1998; *McNinch et al*., 2006] and with respect to the general scholarship regarding shelf sediment transport [*Sumer and Fredsoe*, 2002]. The fusion of high-resolution field data (morphology and hydrodynamics) collected both from surface vessel and AUV can be used to improve our understanding of the response of the seabed to both storm and fair weather flow conditions in a heterogeneous inner-shelf setting, with application to the interpretation of acoustic imagery for surface morphology and textural properties of surficial sediments on the seabed in other similar settings.

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