Observations of wave breaking and surf zone width

from a real-time cross-shore array of wave and current sensors at Duck, NC

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Abstract—**Data from a cross-shore array of acoustic sensors at the US Army Corps of Engineers Field Research Facility is examined for evidence of wave transformation and longshore currents across the surf zone by comparing several events in 2009-10 with different wave statistics. Hurricane Bill (H_s = 3+ m, T_p = 18 s) was a long-period wave event with strong evidence of non-linear wave transformations, and a track that was offshore such that the coast received very little wind. A strong depth-uniform longshore current was observed at the 5 and 6 m sites (up to 1.8 m/s) that was in-phase with the wave energy. Weak currents were measured at the 8 and 11 m depth sites, indicating that the limit of the surf zone extended to between 6 and 8 m depth. Hurricane/Nor'easter Ida (H_s = 5+ m, T_p = 12 s) was a typical large wave event in the fall, with strong winds (wind-sea a major wave component) and rotating wind direction. Hurricane Earl (H_s = 4+ m, T_p = 15 s) was the first major wave event with all sensors in place, since the sensors at the 2 and 3 m depths were added in August 2010.**

For the selected events we present the observations of wave evolution across the surf zone. The offshore extent of wave breaking was determined from Argus Station imagery by analyzing pixel intensity for time exposure images along cross-shore transect. Surf zone widths are compared to the estimated extent of breaking by comparing wave energy across the array and the magnitude of the longshore current. The alongshore momentum balance was estimated to determine the contribution of radiation stress gradients to observed longshore current. The results provide a comparison of the seaward limit of the surf zone and width of the wave-driven current for different wave forcing conditions.

Keywords- waves; currents; real-time observations; hurricanes

I. Introduction

The United State Army Corps of Engineers have established a real-time observation system [1] for waves and currents at Duck, North Carolina. Historically, the Field Research Facility (FRF) site has been a key place for observing the nearshore environment, with a 30+ year dataset of environmental conditions and periodic intensive field experiments with participation by researchers from many academic and governmental institutions. Since 2008 a new system of real-time wave sensors that spans the continental shelf with close spacing in the nearshore has been established, shown in Fig. 1 and listed in Table 1. This includes acoustic wave/current sensors that are cabled to shore along the 560 m long FRF pier in nominal water depths of 5, 6, 8 and 11 m. It also includes directional wave buoys in water depths of 17 and 27 m, and a discus wave buoy in 47 m operated by NOAA (NDBC station 44014). In August 2010 two additional acoustic wave and current sensors were added at nominal water depths of 2 and 3 m near the inner bar. Supplemental to this dataset are images from a system of 7 cameras mounted on a 43 m tower overlooking the beach and nearshore region.

TABLE I. SENSORS IN THE FRF CROSS-SHORE ARRAY

Site	Water Depth (m)	Cross-shore Location[a] (m)	Sensor
A	2	233	Nortek Aquadopp
B	3	375	Nortek Aquadopp
C	5	446	Nortek AWAC
D	6	606	Nortek AWAC
E	8	918	Nortek AWAC
F	11	1303	Nortek AWAC
G	17	3816	Datawell Waverider buoy
H	26	16303	Datawell Waverider buoy
I	47	94500	NOAA 3-meter discus buoy

a. Cross-shore location in the FRF coordinate system, the swash zone is typically near 100 m.

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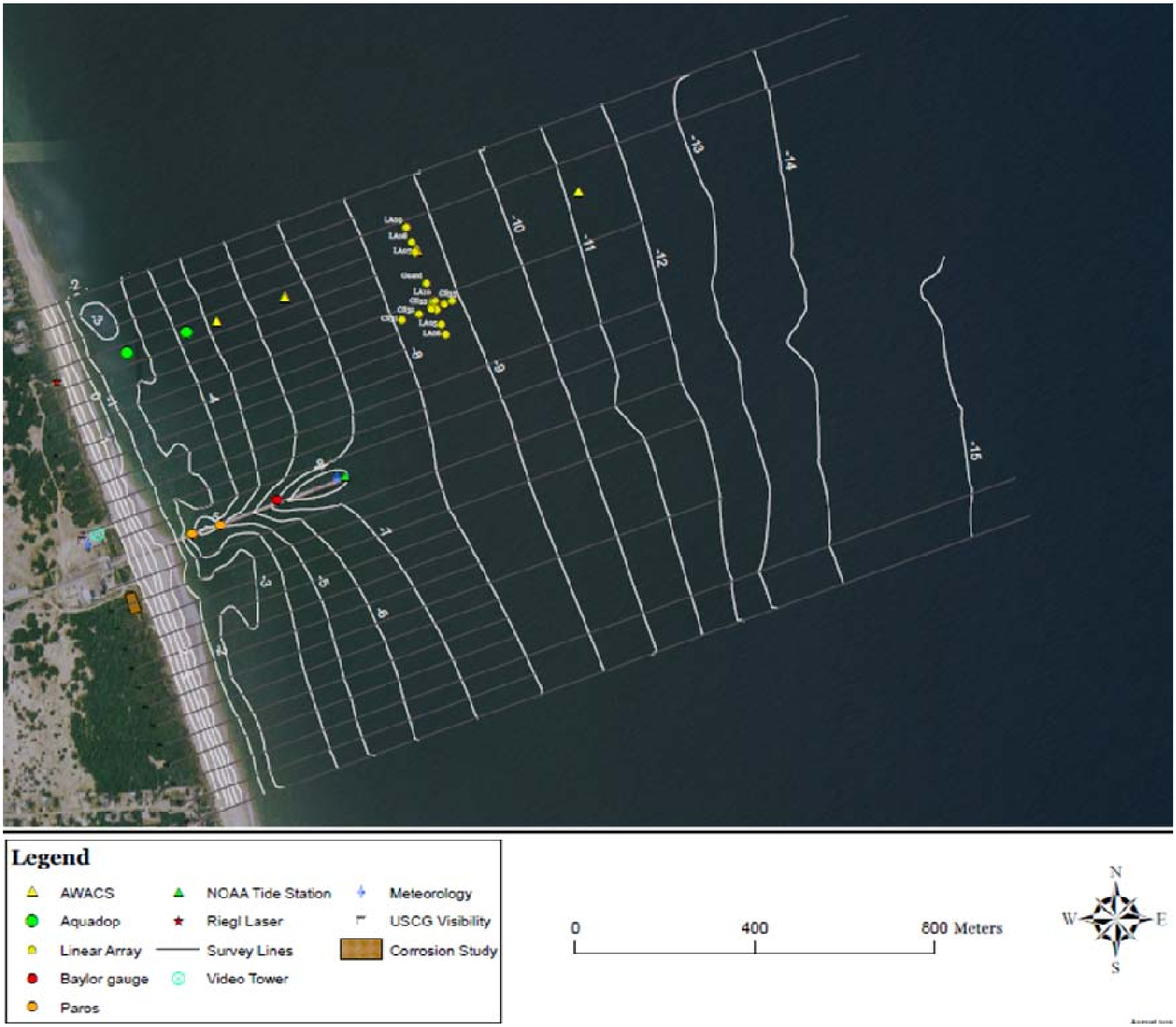

Figure 1. *Map showing FRF instrument sites and bathymetric contours*

The coast of North Carolina is frequently struck by hurricanes [2] and other storm events such as nor'easters, which bring a variety of wind and wave conditions depending on the storm type, intensity and direction. In this paper we compare three large wave events in 2009-10, shown in Fig. 2: (1) Hurricane Bill, (2) Hurricane/Nor'easter Ida, and (3) Hurricane Earl. Hurricane Bill was characterized by light winds (up to 6 m/s), long wave periods (up to 20 s) and significant wave heights (Hs) up to 3.7 m (measured 1300 m offshore at the 11 m AWAC site). Ida was a strong extra-tropical low pressure system with strong winds (up to 20 m/s), a large storm surge (up to 1 m), wave periods up to 12 s and significant wave heights up to 5.5 m. This was a very long duration event with storm conditions persisting for three days. Hurricane Earl had very strong winds (up to 25 m/s), wave periods up to 15 s and significant wave heights up to 4.7 m. This was the first major wave event with all sensors in the cross-shore array in place. In the following sections the observations of waves and currents for each storm are discussed.

In addition to the observations from sensors listed in Table 1, we present video image data of the surf zone from cameras mounted on the tower (Fig. 1). We have developed an algorithm to extract time-series of surf zone widths from Argus Station [3] imagery by analyzing pixel intensity along cross-shore transects. A 10-minute time exposure image is shown in Fig. 3 for Hurricane Bill (1900 UTC August 22 2009, YD 234.8). Black dots indicate five cross-shore pixel transects and red dots represent the limit of the surf zone at that time.

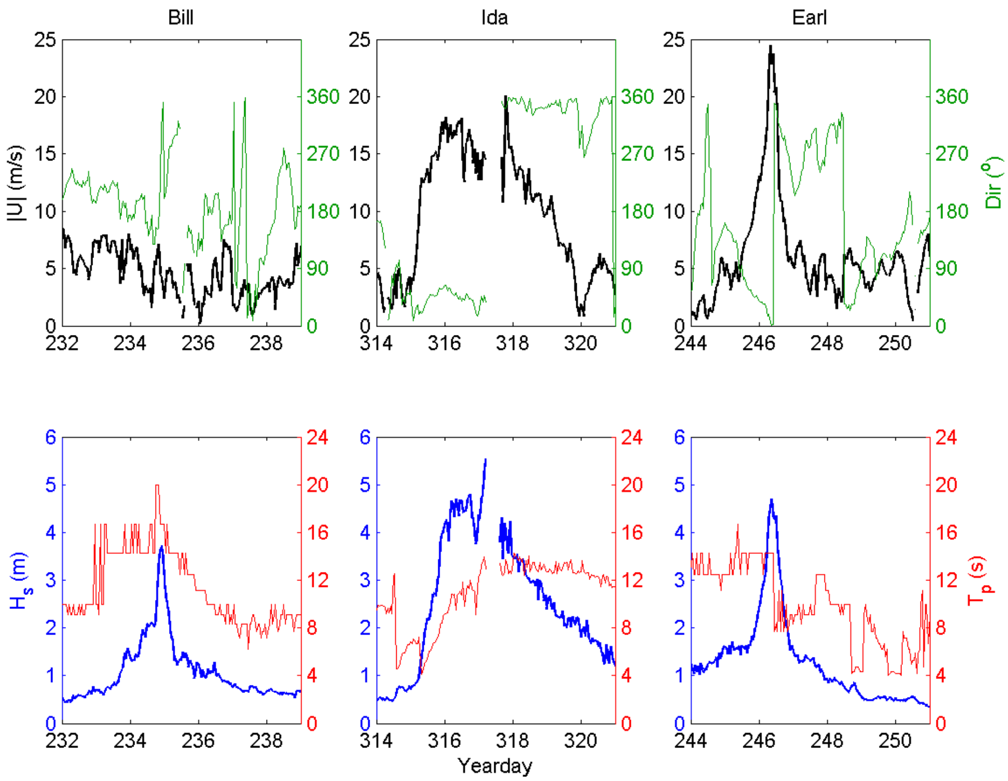

Figure 2. *Wind and wave statistics for the three selected wave events. Wind speed and direction are shown in the upper panels; significant wave height and peak period at the 11 m AWAC site (outside the surf zone) are shown in the lower panels*

II. HURRICANE BILL

Hurricane Bill occurred on Aug. 22-23 2009 (Julian day, or Yearday (YD) 234-235) and the storm track was far from the coast. As a result the winds were light (maximum 6 m/s) at the FRF and the peak wave period was very long, 18-20 s. The significant wave height at the 11 m AWAC site remained over 2 m 12 for hours, and H_s at the peak of the event was 3.7 m. The wave height at the 11 m, 8 m, 6 m, and 5 m depth sites are shown in Fig. 4. At the peak of the event (YD 234.8), the waves shoaled and H_s increased from 3.6 to 4.1 m from the 11 m AWAC to the 8 m AWAC. Depth-induced breaking initiated between the 8 m and the 6 m sites: H_s reduced to 3.2 m at the 6 m AWAC and 3.0 m at the 5 m AWAC. The spectra also indicate that the wave shape was most non-linear within the breaking zone, with up to 4 or 5 harmonics of the spectral peak at the 8 m and 6 m AWAC sites. A strong longshore current was observed at the 5 and 6 m sites (up to 1.8 m/s) that was in-phase with the wave energy (Fig. 4). Weak currents (less than 0.15 m/s) were measured at the 8 and 11 m sites, also indicating that the limit of the surf zone extended to between 6 m and 8 m depth for this event.

The surf zone widths (in the local FRF coordinate system), determined from the Argus camera images, are also shown in Fig. 4. The influence of tidal water level elevations on the initial breaker line is apparent, causing variability of 30-50 m. The visible surf zone width was over 500 m at the peak of the event, therefore extending to between the 5 m and 6 m AWAC sites. Although the video image data is limited by daylight and is interfered with by raindrops on the camera housing window, it provides a useful time-series of surf zone width particularly when viewed together with data at discrete sensor sites across the nearshore.

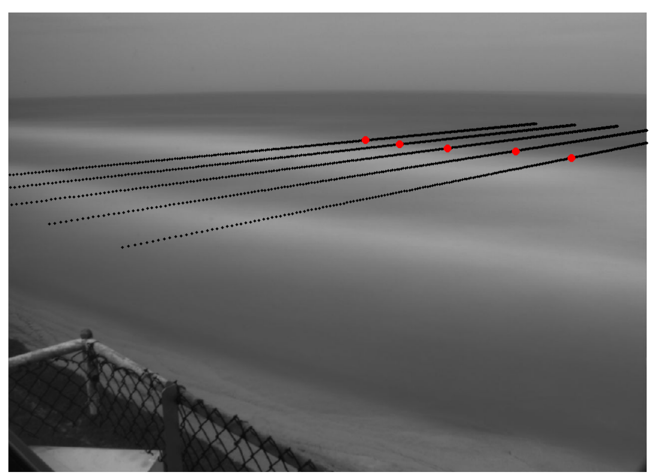

Figure 3. *Argus 10-minute time exposure image taken on 1900 UTC August 22 2009 prior to the peak wave height for Hurricane Bill from camera C3, with pixel transects (black dots) and selected surf zone limit (red dots)*

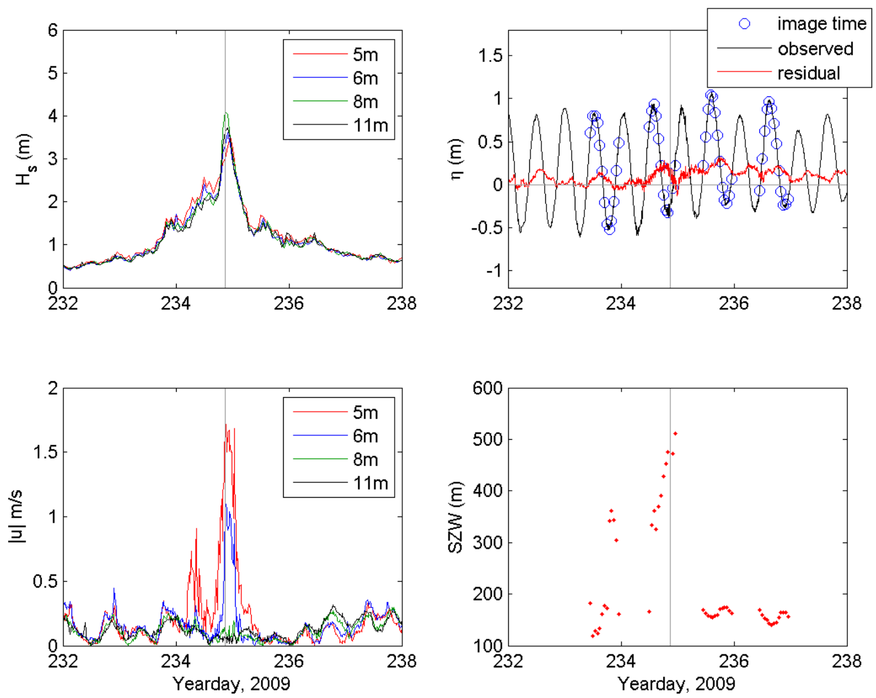

Figure 4. *Hurricane Bill: significant wave height at instrument sites (upper left); observed and residual water levels (upper right); magnitude of the alongshore current component (lower left); surf zone width in the FRF coordinate system estimated from Argus camera imagery (lower right).*

Current profiles, for the alongshore component, are shown in Fig. 5. The current magnitude was generally greater than 0.5 m/s whenever the waves were greater than 2.75 m at the 5 m AWAC site and the currents were depth-uniform inside the surf zone (5 m and 6 m depth sites) with very weak currents outside the surf zone (8 m and 11 m depth sites). This event provides a good example of strong wave-driven currents in the surf zone, with very little influence of tidal or wind processes.

III. Hurricane/Nor'easter Ida

Hurricane Ida made landfall in the Gulf of Mexico, and the remnants of the storm contributed to the development of a separate, strong extra-tropical low pressure system (a nor'easter) that affected the US east coast with strong winds and high rainfall [4]. At the FRF, the storm occurred on November 11-15 2009 (Yearday 315-319) winds were 15-20 m/s from the northeast for three days resulting in 8-12 s period waves (Fig. 1). This long duration event resulted in H_s at the 11m AWAC site of over 4 m 48 for hours, with H_s of 5.5 m at the peak of the event. This type of storm with large waves, strong winds (wind-sea a major wave component), and rotating wind direction occurs frequently in winter and fall months along the outer banks of North Carolina.

Wave heights, water levels, current magnitudes and surf zone widths are shown in Fig. 6. At the peak of the event (YD 317.2) the wave height reduced across the array from 5.5 m (11 m site), 5.0 m (8 m site), 4.2 m, to 3.6 m (5 m site). This

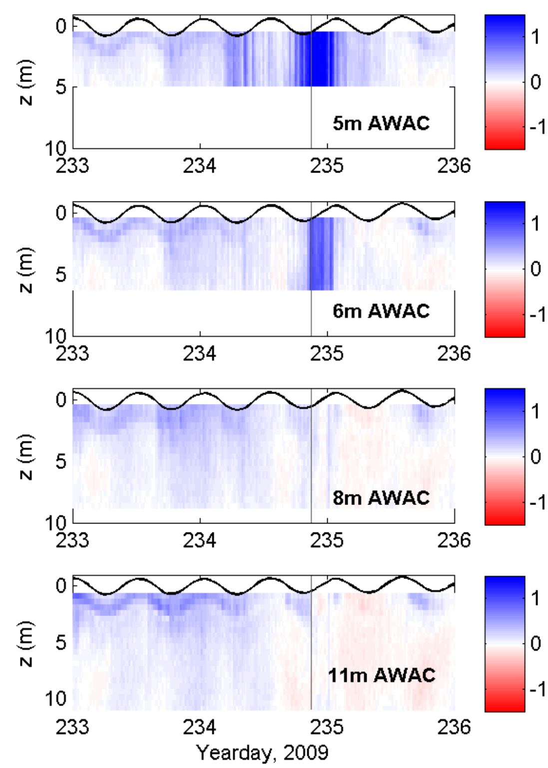

Figure 5. *Vertical distribution of alongshore horizontal currents (m/s) at 4 sites during Hurricane Bill. Positive (blue) indicates a current flowing to the north. The veritical line indicates the time of peak wave energy.*

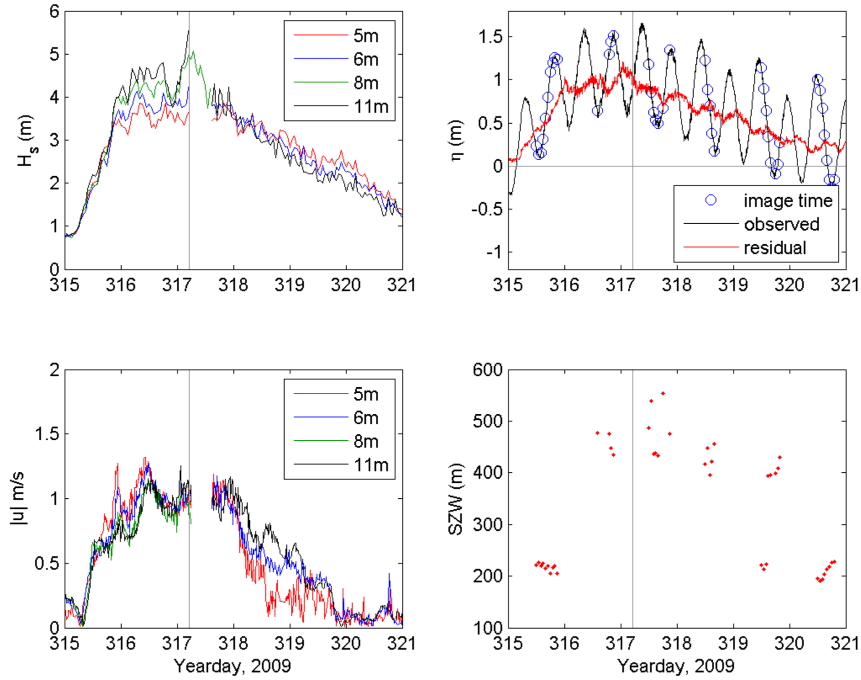

Figure 6. *Hurricane/Nor'easter Ida: significant wave height at instrument sites (upper left); observed and residual water levels (upper right); magnitude of the alongshore current component (lower left); surf zone width in the FRF coordinate system estimated from Argus camera imagery (lower right).*

indicates that breaking may have extended to between the 8 m and 11 m sites, although this occurred during the night and therefore the camera data was not available. The strong onshore winds (Fig. 2) caused the mean water level to increase by up to 1 m (Fig. 6), allowing larger waves to propagate close to shore before breaking than other events. Strong 0.5-1.3 m/s southward alongshore currents were observed during the storm, fairly uniform across the four sensor locations in 5-11 m water depth, indicating a mix of wave- and wind-driven flow.

IV. Hurricane Earl

Hurricane Earl hit the NC coast on September 2-3 2010 (YD 245-246) with very strong winds up to 25 m/s and wave periods up to 14-15 s. The significant wave height at the 11 m depth site remained over 2 m for 18 hours, and H_s at the peak of the event was 4.7 m. This was the first major wave event with all sensors in the cross-shore array in place, since the instruments at the 2 and 3 m depths were added in August 2010. Wave heights, water levels and current magnitudes are shown in Fig. 7. The wave height at the shallowest site was limited to 2.5 m, strongly influenced by the tidal and storm surge induced variations in water depth. The observed currents at the 2 m site were up to 1.5 m/s, and the currents speed decreased at each site offshore. Unfortunately, a problem with the camera power occurred and surf zone images were not collected during the peak of the event.

At the shallower sites (2 m, 3 m, 5 m) the peak current speeds occurred at the time when waves were largest (YD 246.4) and were directed northward, driven by waves. At the 8 m and 11 m sites the peak currents occurred one hour later and were directed southward, driven by winds. The current profiles are shown in Fig. 8, and the alongshore flow direction is indicated by color. The combination of wave- and wind-driven flows in opposing directions produced a reversal in the direction of alongshore flow in the vicinity of the 6 m depth site.

The cross-shore evolution of H_s is shown in Fig. 9. From this data, we can infer wave transformation processes that cause the wave height to increase (generation by wind, or shoaling) or decrease (depth-induced breaking, or dissipation by bottom friction). We plan to use this type of data in further studies focused on wave spectral evolution and compare with numerical models.

V. Alongshore Momentum Balance

In order to compare the relative importance of wave and wind forcing, we examine the alongshore balance of cross-shore momentum in the surf zone for the three events. For Hurricane Bill, there was very little wind and the flow was dominated by the wave forcing. For Nor' Ida, both were important and wind and wave directions were co-aligned. For Hurricane Earl, both were important but wind and wave-driven alongshore flow

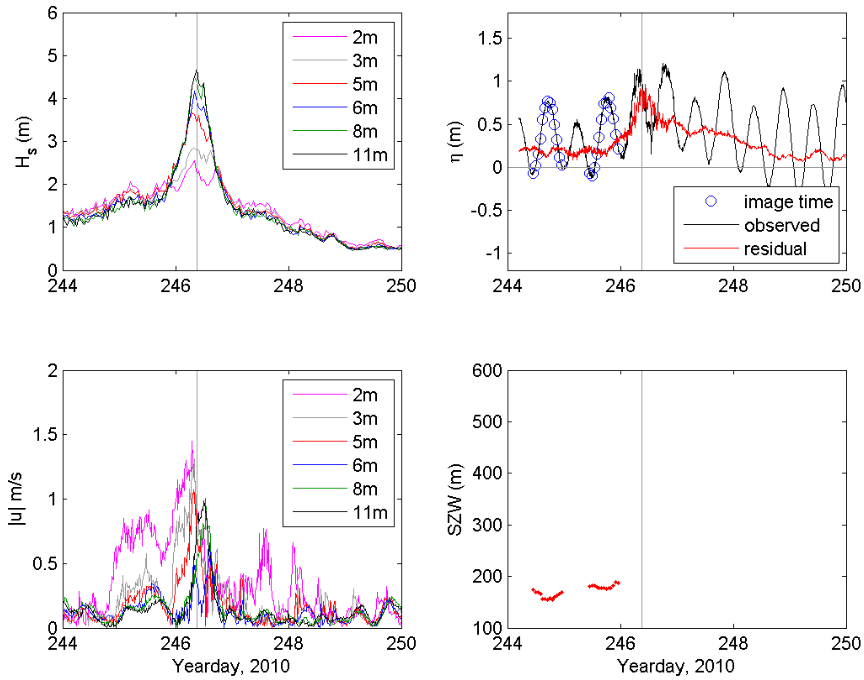

Figure 7. *Hurricane Earl: significant wave height at instrument sites (upper left); observed and residual water levels (upper right); magnitude of the alongshore current component (lower left); surf zone width in the FRF coordinate system estimated from Argus camera imagery (lower right).*

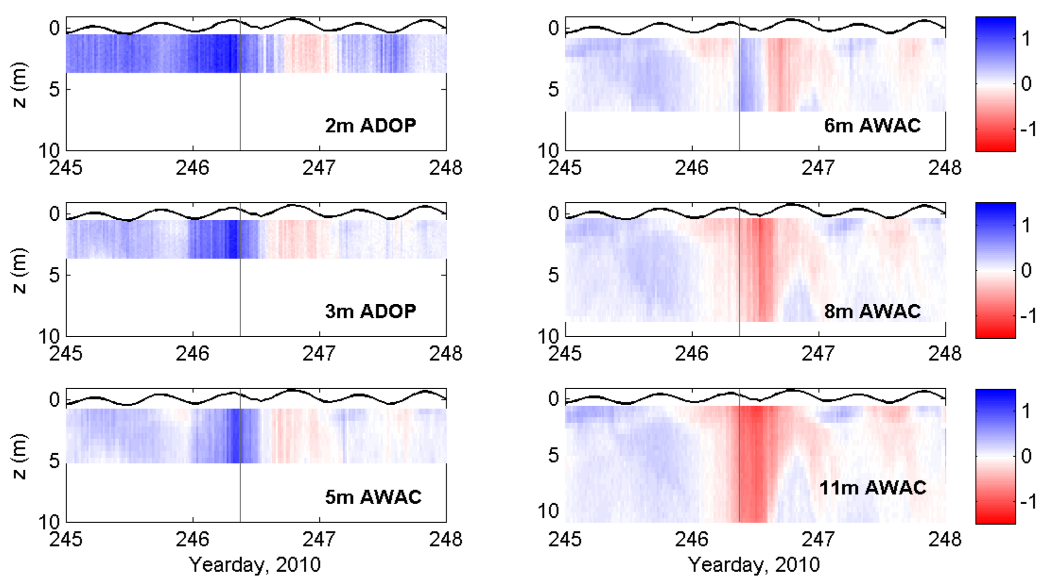

Figure 8. *Vertical distribution of alongshore horizontal currents (m/s) at 6 sites during Hurricane Earl. Positive (blue) indicates a current flowing to the north. The veritical line indicates the time of peak wave energy.*

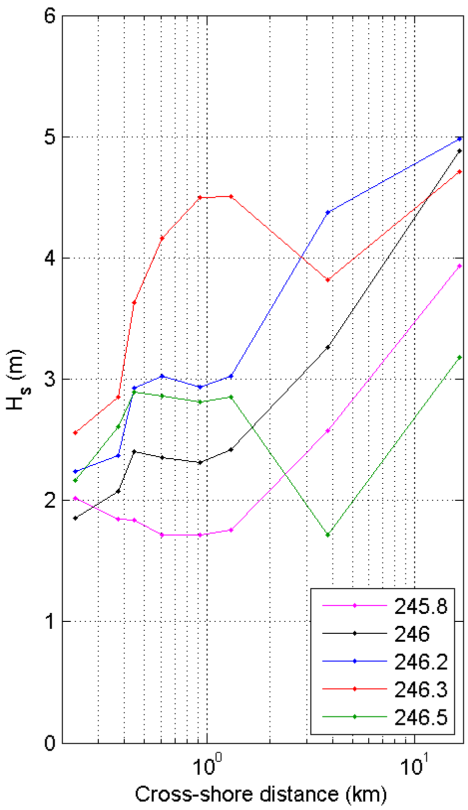

Figure 9. *Significant wave height profiles along the cross-shore array during Hurricane Earl, on Sept 2-3 2010 (YD 245-246).*

directions were opposed. Following the approach of [5], we define a coordinate system with x directed offshore and y alongshore to the north ($+v$ is the northward alongshore current). The alongshore momentum balance is given by:

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + fu = -\frac{1}{\rho}\frac{\partial P}{\partial y} + \frac{\tau_s^y}{\rho h} - \frac{\tau_b^y}{\rho h} - \frac{1}{\rho h}\frac{\partial S_{xy}}{\partial x} \quad (1)$$

where t is time, f is the Coriolis parameter, P is pressure, ρ is a reference water density, τ_s^y is the alongshore component of wind stress, τ_b^y is the alongshore component of bottom stress, S_{xy} is the wave-induced radiation stress [6] and h is water depth. Assuming steady-state ($\partial/\partial t = 0$), no cross-shore currents ($u = 0$) and no gradients in the alongshore direction ($\partial/\partial y = 0$), this reduces to an approximate balance between the wind stress, the bottom stress and the cross-shore gradient in wave radiation stress:

$$0 = +\frac{\tau_s^y}{\rho_o h} - \frac{\tau_b^y}{\rho_o h} - \frac{1}{\rho_o h}\frac{\partial S_{xy}}{\partial x} \quad (2)$$

The bottom stress is:

$$\tau_b^y = \rho c_f v_b |v_b| \quad (3)$$

where c_f is a bed shear stress coefficient and v_b is the alongshore velocity at the bed.

The wind stress is given by:

$$\tau_s^y = \rho_a C_D V|V| \quad (4)$$

where ρ_a is air density, C_D is an atmospheric drag coefficient and V is the alongshore wind speed. The alongshore component of cross-shore momentum is:

$$S_{xy} = E(\cos(\theta)\sin(\theta)) \quad (5)$$

where E is wave energy (proportional to the wave height) and θ is the wave direction with respect to the offshore normal. We evaluate the radiation stress gradient across the surf zone between the 8 m and 5 m AWAC sites (Δx = 477 m) at the time of peak wave conditions for each event, and the results are listed in Table 2. The order of magnitude estimates of bottom stress and wind stress momentum terms, also given in Table 2, were evaluated at the 5 m AWAC site using canonical values for the bed shear stress and atmospheric drag coefficients of 0.0023 (although c_f may vary across the surf zone [7]). The results indicate that each event had a different balance between momentum terms, resulting in different alongshore currents. During Bill the wind momentum was negligible and the balance existed between radiation stress and bottom friction, with a purely wave-driven longshore current (Fig. 5). During Ida both wind and wave momentum contributed to driving the southward alongshore current. During Earl, wind and wave momentum were opposed and the resulting flow at the 5 m AWAC site was weaker than during Hurricane Bill even though the radiation stress gradient was greater. Observations during Earl (Fig. 8) indicated that shoreward of the 5 m depth site the flow was northward (wave-dominated), while seaward of the 5 m depth site the flow was southward (wind-dominated).

TABLE II. ALONGSHORE MOMENTUM BALANCE

Term	Momentum at the 5 m site (m/s^2)[a]		
	Hurricane Bill YD 234.9, 2009	***Nor' Ida YD 316.4, 2009***	***Hurricane Earl YD 246.3, 2010***
wind	-10^{-5}	-10^{-3}	-10^{-3}
wave	$+10^{-3}$	-10^{-3}	$+10^{-3}$
bottom	$+10^{-3}$	-10^{-3}	$+10^{-4}$

a. + indicates alongshore northward

VI. SUMMARY AND CONCLUSIONS

Wave and current data from an array of cross-shore sensors at the US Army Corps of Engineers Field Research Facility in Duck, NC, were examined for three storm events with a range of wind and wave conditions. Wave characteristics and current profiles were compared for sensors located across the surf zone in nominal water depths of 2-11 m. In addition, the width of the surf zone was determined from time lapse Argus camera imagery. The results indicate that each event had a different balance between momentum terms, resulting in different alongshore currents ranging from a purely wave-driven longshore current (Hurricane Bill, Aug. 2009) to equal contributions to an alongshore flow (Nor'easter Ida, Nov. 2009) to opposing wind- and wave-driven currents (Hurricane Earl, Sep. 2010). The data set will allow other events to be analyzed and compared with predicative numerical models of wave transformation and forcing of currents in the surf zone.

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