CDIP wave observations during Hurricanes Irma, Jose, and Maria, and a nor'easter

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ABSTRACT

The Coastal Data Information Program (CDIP) recorded detailed information about the waves generated by Hurricanes Irma, Jose, and Maria in September 2017, and the January 2018 Bomb Cyclone Nor'easter. The wave fields generated by these storms were measured by an along-coast array comprised of twenty Datawell Directional Waverider moored buoys in the CDIP network. Significant wave height records and maximum individual waves are the focus of this report. The complete quality-controlled directional spectra and displacement data sets, as well as sea surface temperature data, are publicly available at http://cdip.ucsd.edu .

ADDITIONAL KEYWORDS: Wave measurements, significant wave height, maximum wave height, WaveWatch III.

The 2017 Atlantic hurricane season was the most active since 2005, based on the Accumulated Cyclone Energy index[1]. A detailed record of the waves generated by these storms was obtained by the Coastal Data Information Program (CDIP). CDIP is an extensive wave monitoring network along United States coastlines that is primarily funded by the U.S. Army Corps of Engineers (USACE). Several locations analyzed in this report are cost shared with the U.S. Navy, industry, and National Oceanic Atmospheric Administration's U.S. Integrated Ocean Observing System (NOAA IOOS).

Waves generated during Hurricanes Irma, Jose, and Maria were measured by CDIP's Datawell Waverider buoys moored at locations shown in Figures 1, 3, and 5, respectively, spanning a north-south distance of ~2,700 km. The buoys report their time series of wave observations in ~30-minute segments via satellite transmissions. These data streams are converted into a variety of standardized data products (bulk properties, 1-dimensional and directional wave spectra, etc.) by CDIP at the Scripps Institution of Oceanography, University of California, San Diego, and are available in near-real time at http://cdip.ucsd.edu.

Using a traditional measure of wave intensity, Hs (significant wave height, defined as the average height of the one-third highest waves in a given interval of time), the temporal evolution of the storm wave height at each of the buoy locations for each storm is shown in Figures 2, 4, and 6. During Hurricane Irma, five

1) http://www.noaa.gov/media-release/extremely-active-2017-atlantic-hurricane-season-finally-ends.

Table 1.
Maximum recorded wave heights during Hurricane Irma, September 2017 (listed from south to north).

Station name	UTC (DD-HH)	Hmax (m)	Tmax (s)	Hs (m)	Tp (s)	Dp (deg)	Delay (hr)	Hmax/ Hs	Hmax/ depth	Depth (m)
Rincon, PR	07-08	8.16	10.9	4.02	9.9	337	1.4	2.03	0.25	33
Pulley Ridge, FL	10-23	12.63	10.2	6.76	10.5	007	0.9	1.87	0.17	75
Fort Pierce, FL	11-00	11.91	10.2	6.43	9.9	107	-1.2	1.85	0.74	16
Cape Canaveral, FL	11-05	7.19	10.2	4.32	11.8	125	-1.2	1.66	0.72	10
St. Augustine, FL	11-08	12.25	9.4	6.93	11.8	092	-1.9	1.77	0.51	24
Fernandina Beach, FL	11-16	11.30	10.9	5.65	13.3	116	4.7	2.00	0.75	15
Wilmington Harbor, NC	11-21	4.98	7.0	2.76	10.5	149	-5.9	1.80	0.38	13
Masonboro Inlet, NC	11-17	6.95	7.0	3.00	7.7	098	1.3	2.32	0.41	17

UTC: Universal Coordinated Time day and hour of Hmax arrival, October 2016
Hmax: Amplitude (trough-to-crest) of largest recorded individual wave
Tmax: Period of Hmax wave
HS: Significant wave height at time of Hmax arrival
Tp: Peak period corresponding to the measured Hs
Dp: Peak direction corresponding to the measured Hs (meteorological convention)
Delay: Time elapsed between Hs max and Hmax; Delay > 0 means Hmax occurred after Hs max
Hmax / Hs: Ratio of Hmax to Hs during the time interval of Hmax arrival
Depth: Water depth at buoy station

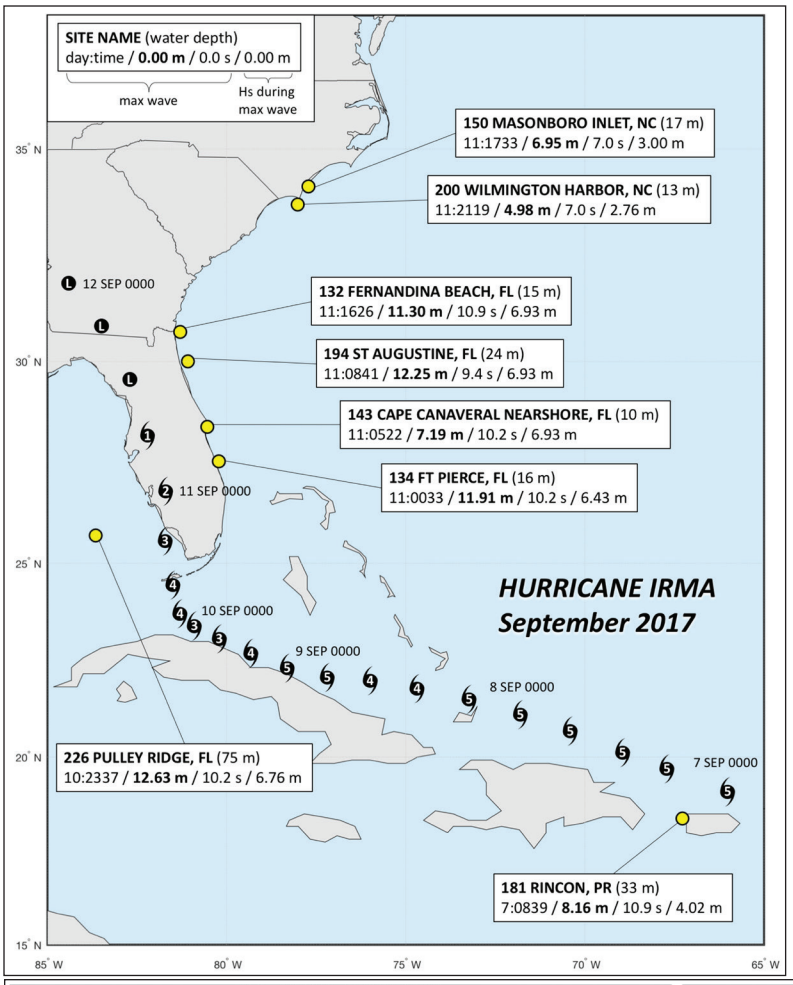
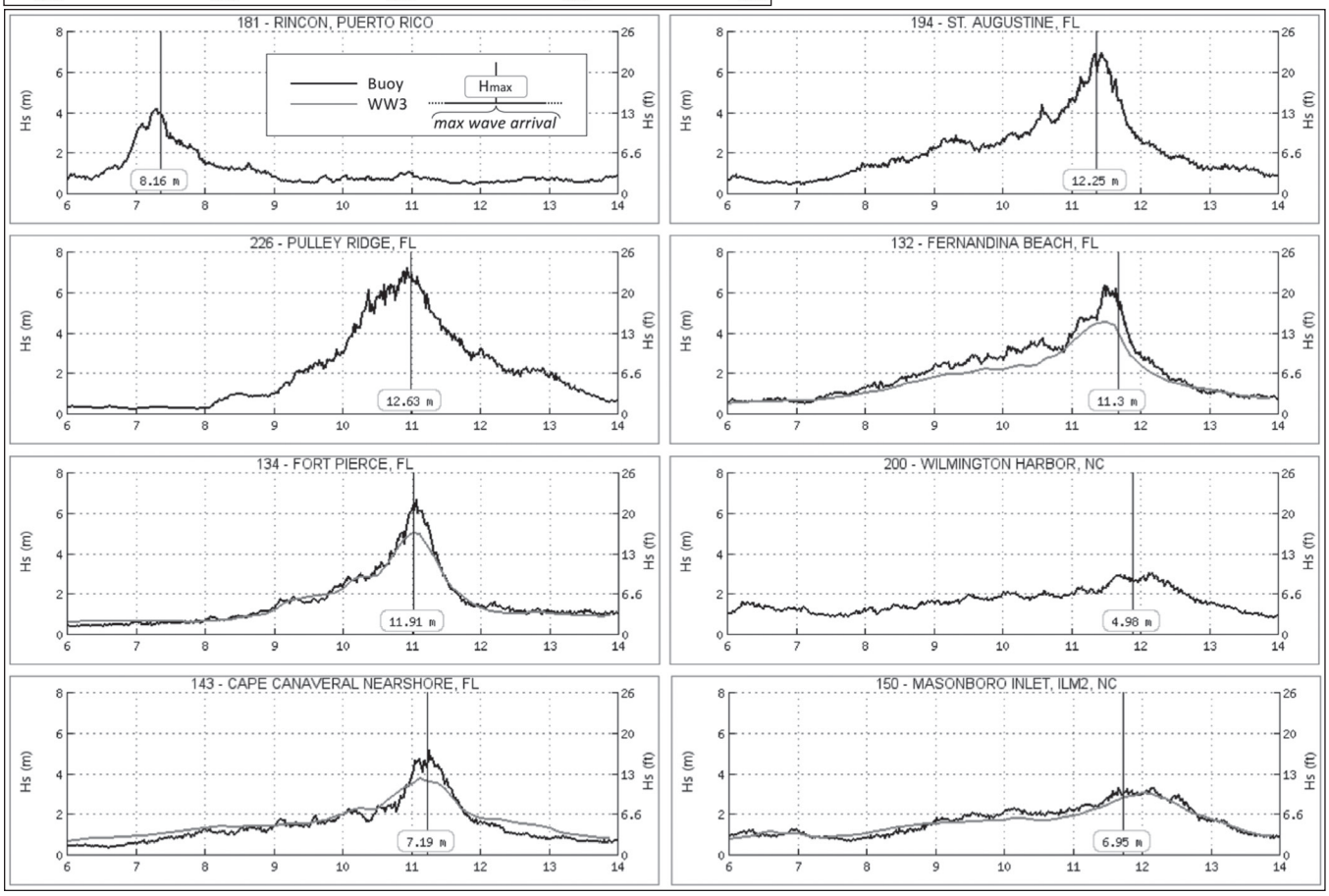


Figure 1 (left). Locations of CDIP wave buoys exposed to Hurricane Irma, with maximum wave details. Eye locations and storm intensities from NOAA's National Hurricane Center. All dates and times are UTC September 2017.

Figure 2 (below). Significant wave height (Hs) measured by CDIP wave buoys during Hurricane Irma, 6-13 September 2017 (all times UTC), with Hmax arrival times and amplitudes indicated. Where available, NOAA's operational WW3 hindcast is shown.



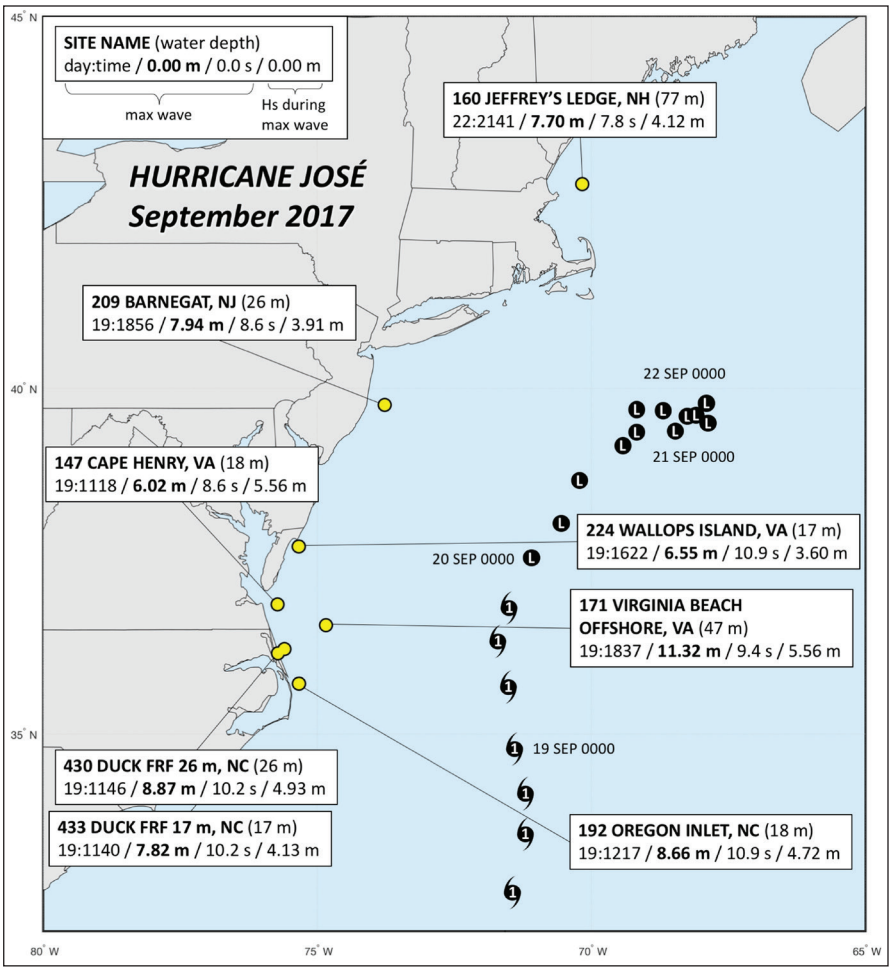
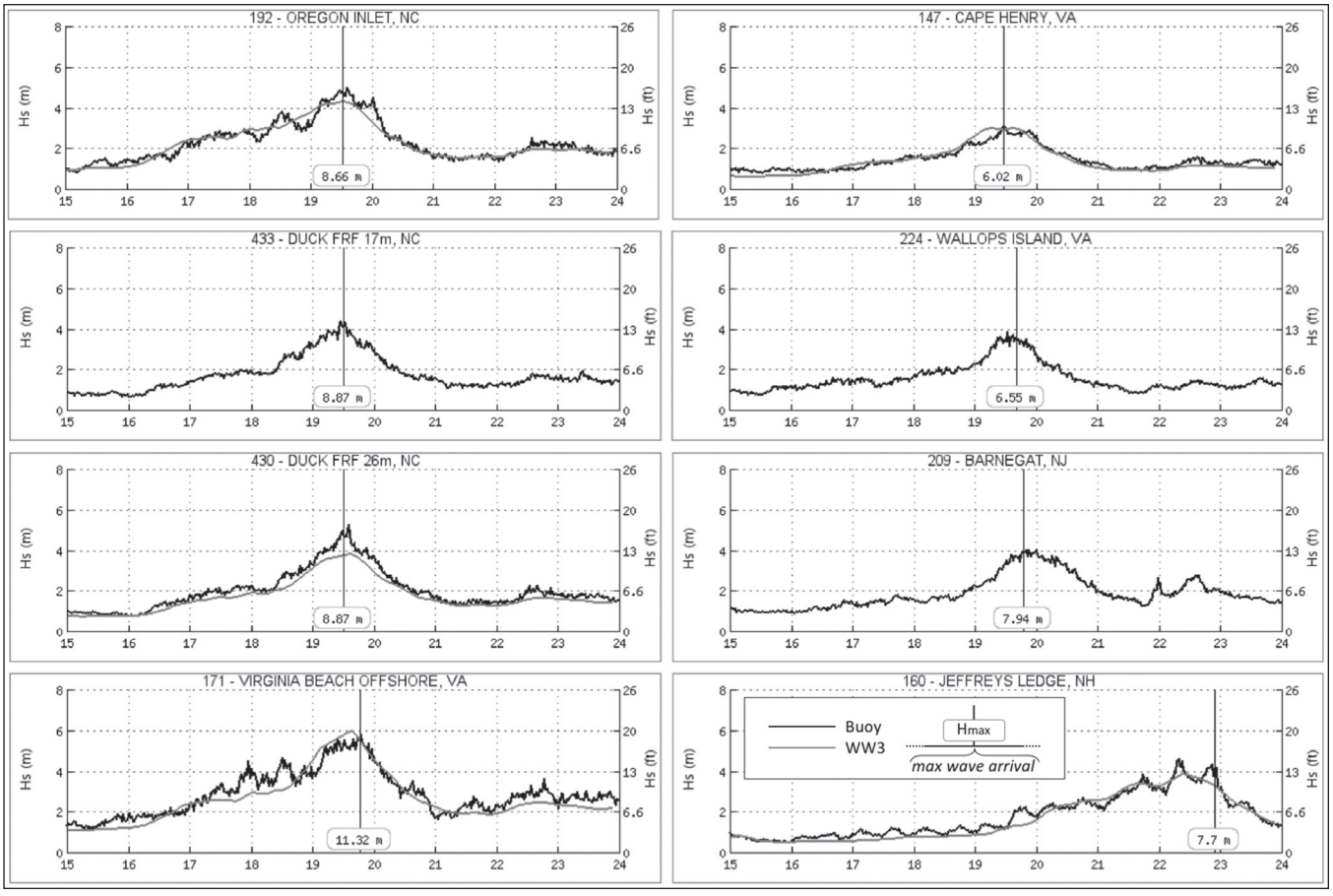


Figure 3 (right). Locations of CDIP wave buoys exposed to Hurricane Jose, with maximum wave details. Eye locations and storm intensities from NOAA's National Hurricane Center. All dates and times are UTC September 2017.

Figure 4 (below). Significant wave height (Hs) measured by CDIP wave buoys during Hurricane Jose, 15-23 September 2017 (all times UTC), with Hmax arrival times and amplitudes indicated. Where available, NOAA's operational WW3 hindcast is shown.



Florida stations recorded their greatest Hs values since initial deployment: Fort Pierce (11 years), Cape Canaveral (11 years), Fernandina Beach (11.5 years), Pulley Ridge (1.0 years) and St. Augustine (0.5 years) all reached new maxima. Hurricane Maria generated the largest waves recorded at Rincon, Puerto Rico (6.4 years). Despite the intensity of the storms, all buoys remained functional and all moorings remained intact, except for the mooring at Rincon, PR, which failed during Hurricane Maria due to abrasion near the seabed anchor connection following several hours of Hs > 6 m.

Where available, Hs values from NOAA's Operational WaveWatch III (WW3) model[2] are included for comparison. WW3 model runs are available every three hours and start with a nine hour hindcast. Presented here is the nine-hour hindcast value for each time step, since it represents the best-informed WW3 model output available.

The most energetic waves have the greatest impact on storm surge, run-up, erosion, and along-shore sediment transport, giving the largest wave in each of the buoy hurricane records (Hmax)

2) http://polar.ncep.noaa.gov/waves/.

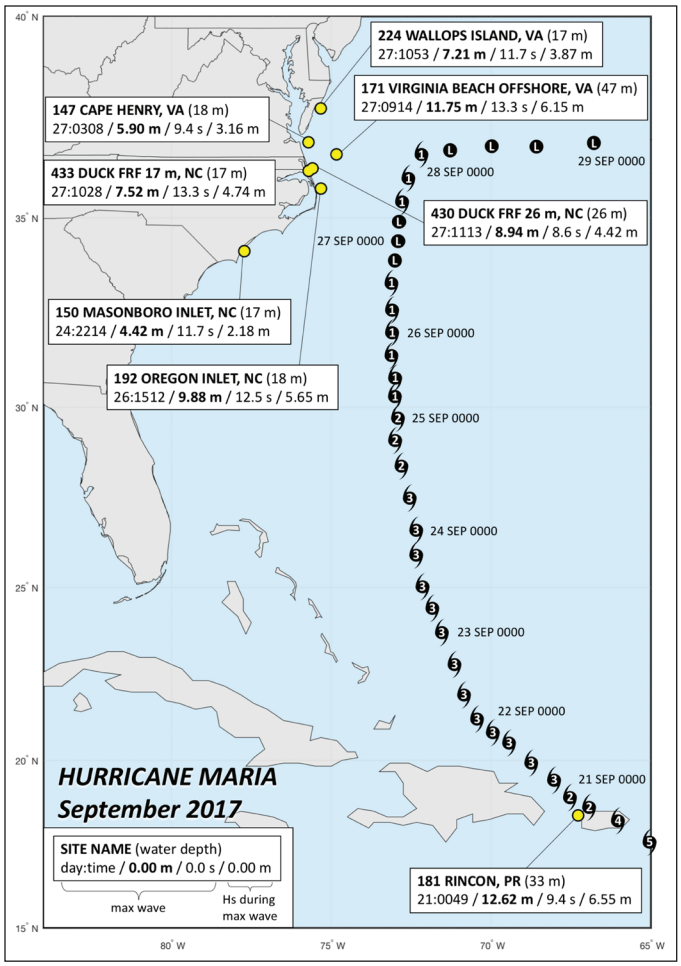


Figure 5 (left). Locations of CDIP wave buoys exposed to Hurricane Maria, with maximum wave details. Eye locations and storm intensities from NOAA's National Hurricane Center. All dates and times are UTC September 2017.

Figure 6 (below). Significant wave height (Hs) measured by CDIP wave buoys during Hurricane Maria, 19-29 September 2017 (all times UTC), with Hmax arrival times and amplitudes indicated. Where available, NOAA's operational WW3 hindcast is shown.

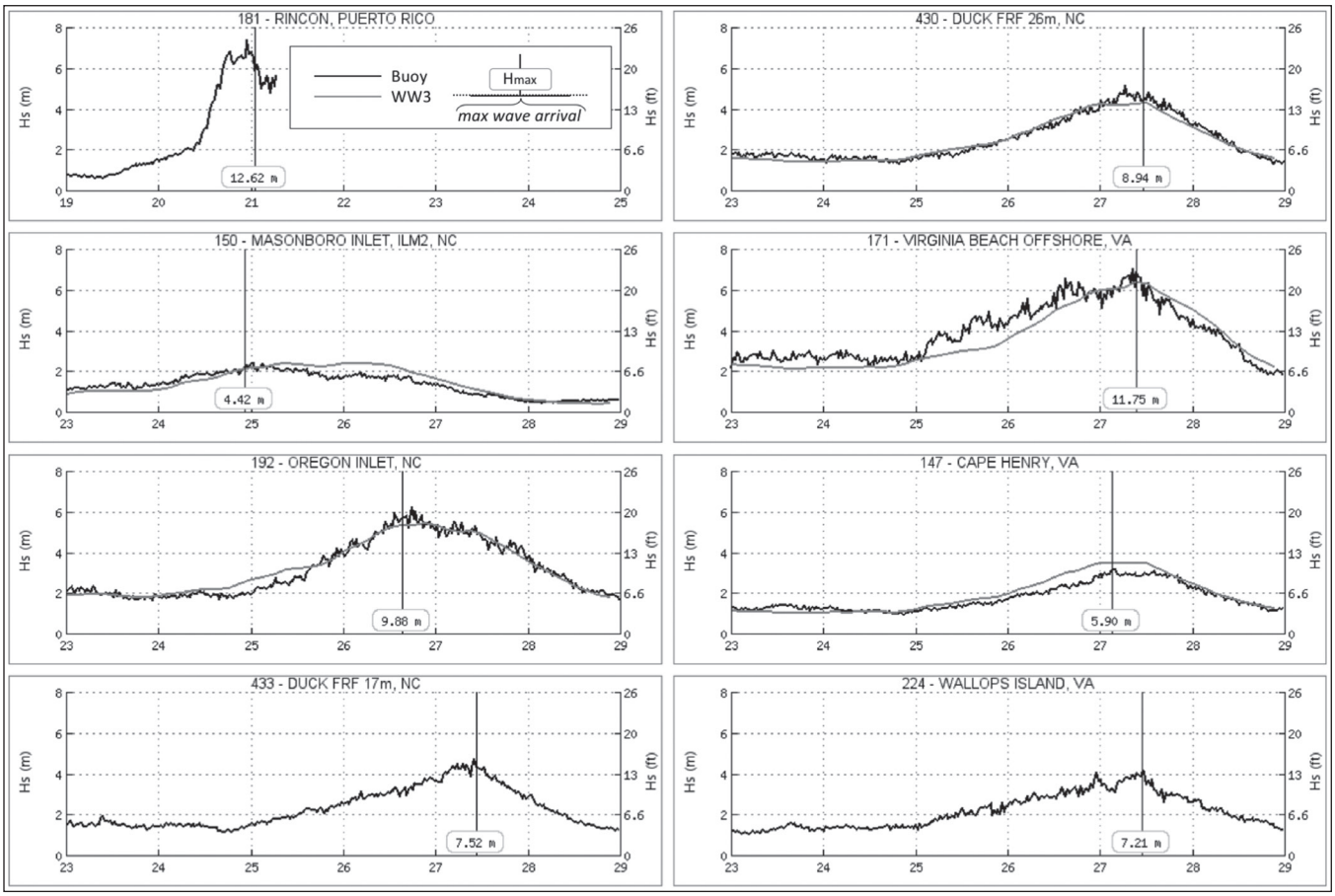


Table 2.

Maximum recorded wave heights during Hurricane Jose, September 2017 (listed from south to north). See table 1 for parameter details.

Station name	UTC (DD-HH)	Hmax (m)	Tmax (s)	Hs (m)	Tp (s)	Dp (deg)	Delay (hr)	Hmax /Hs	Hmax /depth	Depth (m)
Oregon Inlet, NC	19-12	8.66	10.9	4.72	13.3	068	-2.3	1.83	0.48	18
Duck 17 m, NC	19-11	7.82	10.2	4.13	13.3	085	-1.1	1.89	0.46	17
Duck 26 m, NC	19-11	8.87	10.2	4.93	13.3	096	-2.5	1.80	0.34	26
Virginia Beach, VA	19-18	11.32	9.4	5.56	9.9	047	-0.6	2.04	0.24	47
Cape Henry, VA	19-11	6.02	8.6	3.11	13.3	089	0.1	1.94	0.33	18
Wallops Island, VA	19-16	26.55	10.9	3.60	13.3	106	3.1	1.82	0.39	17
Barnegat, NJ	19-18	7.94	8.6	3.91	12.5	123	-2.3	2.03	0.31	26
Jeffrey's Ledge, NH	22-21	7.70	7.8	4.12	9.9	114	13.9	1.87	0.10	77

Table 3.

Maximum recorded wave heights during Hurricane Maria, September 2017 (listed from south to north). See table 1 for parameter details.

Station name	UTC (DD-HH)	Hmax (m)	Tmax (s)	Hs (m)	Tp (s)	Dp (deg)	Delay (hr)	Hmax /Hs	Hmax /depth	Depth (m)
Rincon, PR	21-00	12.62	9.4	6.55	11.1	307	1.6	1.93	0.38	33
Masonboro Inlet, NC	24-22	4.42	11.7	2.18	14.3	134	-2.0	2.03	0.26	17
Oregon Inlet, NC	26-15	9.88	12.5	5.65	14.3	113	-2.8	1.75	0.55	18
Duck 17 m, NC	27-10	7.52	13.3	4.74	14.3	096	0.2	1.59	0.44	17
Duck 26 m, NC	27-11	8.94	8.6	4.42	12.5	107	4.4	2.02	0.34	26
Virginia Beach, VA	27-09	11.75	13.3	6.15	13.3	107	0.5	1.91	0.25	47
Cape Henry, VA	27-03	5.90	9.4	3.16	13.3	114	-1.1	1.87	0.33	18
Wallops Island, VA	27-10	7.21	11.7	3.87	13.3	131	-0.4	1.86	0.42	17

Table 4.

Maximum recorded wave heights during the Bomb Cylcone Nor'Easter, January 2018 (listed from south to north). See table 1 for parameter details.

Station name	UTC (DD-HH)	Hmax (m)	Tmax (s)	Hs (m)	Tp (s)	Dp (deg)	Delay (hr)	Hmax /Hs	Hmax /depth	Depth (m)
Onslow Bay, NC	04-06	7.59	7.0	3.63	7.1	333	-4.1	2.09	0.25	30
Oregon Inlet, NC	04-12	10.13	7.8	5.80	7.7	355	-3.8	1.75	0.56	18
Duck FRF 17m, NC	04-07	7.57	7.8	4.00	9.1	090	-0.8	1.89	0.45	17
Duck FRF 26m, NC	04-11	10.27	7.8	5.30	8.3	016	2.1	1.94	0.40	26
Virginia Beach, VA	04-16	13.74	8.6	6.83	10.5	016	2.8	2.01	0.29	47
Cape Henry, VA	04-11	8.02	7.0	4.28	8.3	061	-1.1	1.87	0.45	18
Cape Charles, VA	04-08	6.11	7.0	3.46	8.3	083	-3.5	1.77	0.49	12.5
Wallops Island, VA	04-11	5.85	8.6	3.16	9.1	083	1.9	1.85	0.34	17
Barnegat, NJ	04-21	8.81	7.8	4.45	11.8	088	5.1	1.98	0.34	26
Block Island, RI	04-19	12.53	8.6	5.32	11.8	128	-1.3	2.36	0.25	50
Cape Cod Bay, MA	04-20	7.89	7.8	3.94	9.1	001	-0.2	2.00	0.30	26
Jeffrey's Ledge, NH	04-22	14.72	10.2	7.78	10.5	067	0.0	1.89	0.19	77

particular significance. These values are shown in Tables 1-3, and were calculated as the maximum wave height in the buoy displacement record. Following the example of Seymour and Castel (2017), the largest vertical displacement of either crest-leading or crest-following wave types was selected as the most valuable datum. Breaking waves create spurious large amplitude peaks and long period oscillations in the computed displacements; these were identified and filtered from the record through visual review of the time series. Hmax for all buoys and storms was found to be less than six times the standard deviation of the 30-minute data segment it occurred within. Only data from Rincon, PR during Hurricane Maria showed evidence of breaking waves while also indicating a peak vertical displacement < 6 times the standard deviation.

Hmax arrival times for the hurricanes are listed in Tables 1-3 and Figures 1, 3, and 5 and plotted in Figures 2, 4, and 6. Note that Hmax did not occur simultaneously with maximum Hs in most cases; the time offset between Hmax and the center of the 30-minute record that produced maximum Hs is listed in Table 1 as "Delay." Hmax/Hs ratios were found range from 1.7 to 2.3, with a mean and median of ~1.9. Hmax/depth ratios at several nearshore locations approach the limit for a solution[3]. The largest individual waves that were recorded by the array during the September 2017 hurricanes

3) USACE, EM 1110-2-1100 (Part II), 1 Aug 08 (Change 2), II-1-37

Table 5.

Comparison of maximum significant wave height (Hs max) values between buoy data and WW3 model output during Hurricanes Irma, Jose and Maria in September 2017 and the January 2018 Bomb Cyclone Nor'Easter (listed from south to north). ΔHs is in meters, and a positive value means buoy Hs max data value is greater than WW3 output. Δt is in hours, and a positive value means buoy Hs max occurred later than WW3 Hs max. Note that buoy data are available every 30 minutes and WW3 output every 3 hours.

	IRMA		JOSE		MARIA		NOR'EASTER	
Station name	**ΔHs**	**Δt**	**ΔHs**	**Δt**	**ΔHs**	**Δt**	**ΔHs**	**Δt**
Fort Pierce, FL	**1.67**	1.5						
Cape Canaveral, FL	**1.40**	3.4						
Fernandina Beach, FL	**1.88**	-0.5						
Masonboro Inlet, NC	**0.28**	-8.0			**0.01**	-24.0		
Onslow Bay, NC							**0.80**	1.5
Oregon Inlet, NC			**0.72**	2.3	**0.82**	-3.1	**1.09**	-1.6
Duck FRF 17m, NC							**1.82**	-1.5
Duck FRF 26m, NC			**1.47**	-0.9	**0.88**	-5.4	**1.90**	0.3
Virginia Beach, VA			**-0.17**	4.0	**0.67**	-0.5	**1.86**	1.5
Cape Henry, VA			**0.11**	-3.9	**-0.32**	-8.0	**1.60**	0.0
Cape Charles, VA							**1.10**	2.9
Wallops Island, VA							**1.00**	-3.0
Barnegat, NJ							**1.31**	-2.0
Block Island, RI							**1.03**	-3.2
Cape Cod Bay, MA							**0.43**	-0.5
Jeffrey's Ledge, NH			**0.73**	-1.4			**2.50**	1.2

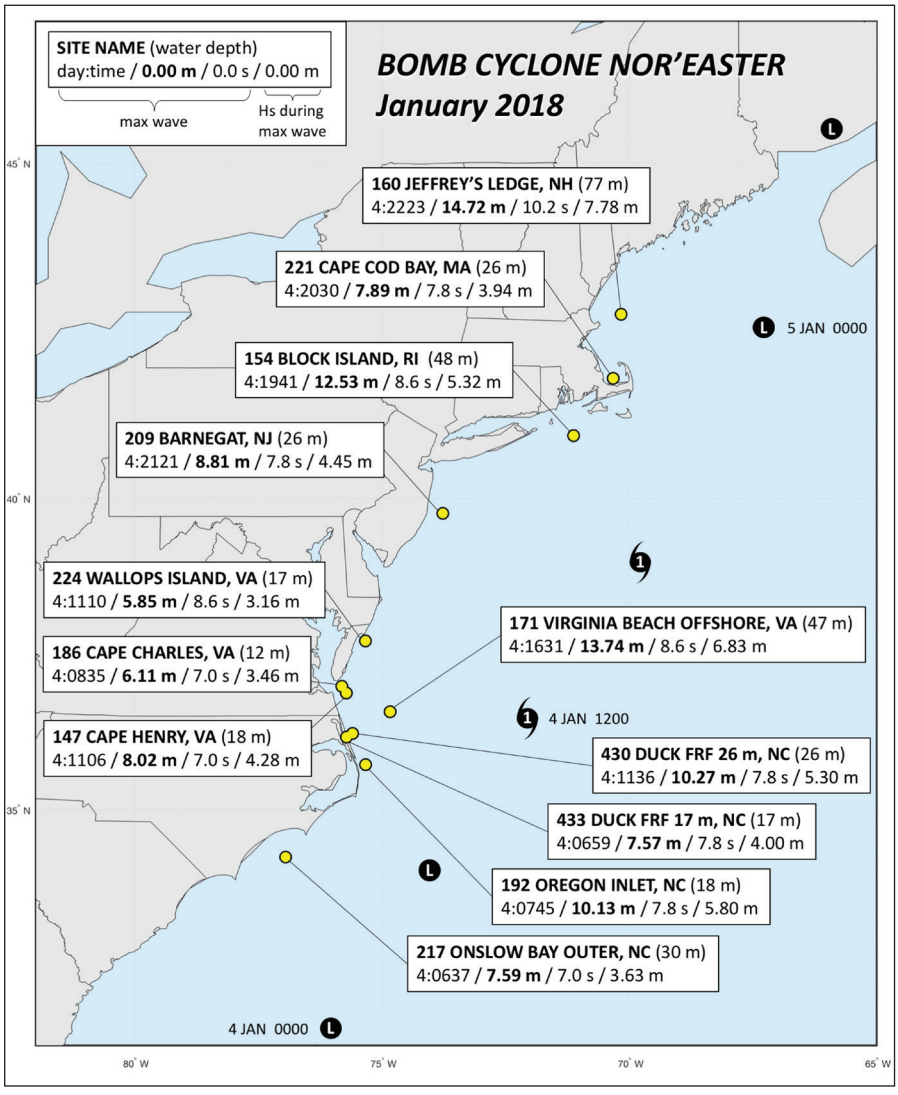


Figure 7 (left). Locations of CDIP wave buoys exposed to the January 2018 Bomb Cyclone Nor'easter, with maximum wave details. Eye locations and storm intensities from NOAA's National Hurricane Center. All dates and times are UTC January 2018.

were 12.6 m at Pulley Ridge, FL, during Irma, and at Rincon, PR, during Maria.

In early January, 2018, a "Bomb Cyclone" nor'easter developed and progressed along the Atlantic coast and ushered in an energetic North Atlantic winter storm season. The storm generated wave heights similar to, and in some locations in excess of, those caused by the hurricanes (Table 4, Figure 7), despite moving more quickly up the coast. Storm waves exceeded the WW3 model at all buoy locations (Figure 8). All moorings remained intact.

At most locations during all storms, the maximum significant wave height (Hs max) measured by the buoys significantly exceeded the Hs max from WW3 output (Table 5). On average, the buoy Hs max was 1.27 times the WW3 Hs max. Arrival time of Hs max as measured by the buoys was often off by several hours from the WW3 Hs max time during the hurricanes.

The 2017 Atlantic hurricane season was the strongest on record since the

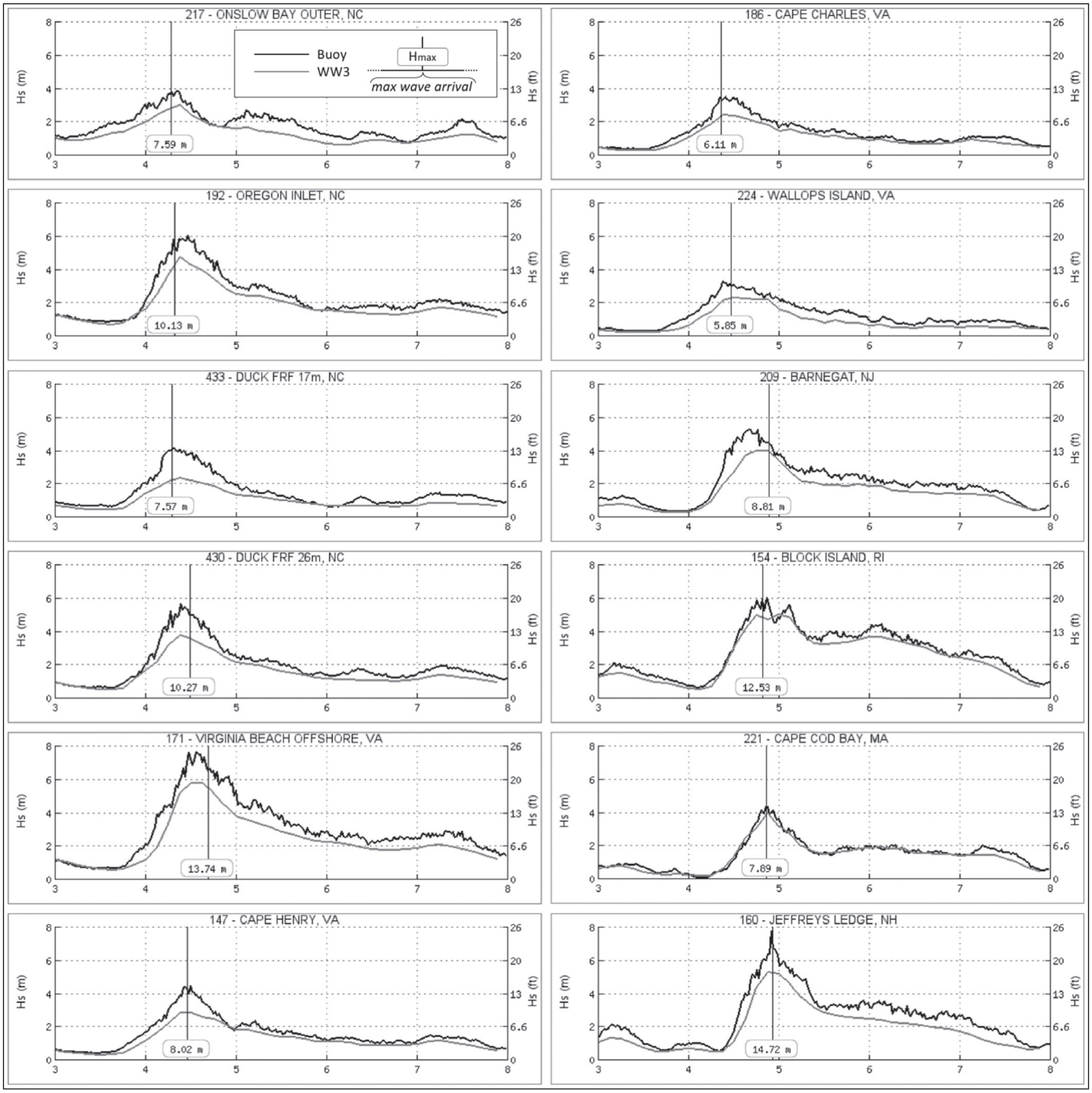


Figure 8. Significant wave height (Hs) measured by CDIP wave buoys during the Bomb Cyclone Nor'easter, January 3-7, 2018 (all times UTC), with Hmax arrival times and amplitudes indicated. NOAA's operational WW3 hindcast is also shown.

CDIP wave buoy network was established on the east coast, and was followed by an exceptionally strong winter storm season. Deficiencies in forecasting nearshore wave conditions during these storms of significance are shown to exist in WW3, with implications for forecasting shoreline response. Our observations identify the need for maintaining high-quality wave measurement instrument arrays in order to understand spatial variability in the wave climate during extreme events. Significant wave height and maximum wave height values are presented here to provide an overview of the rich and detailed data set of wave buoy storm observations publicly available at http://cdip.ucsd.edu.

REFERENCES

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