CDIP observations of recent extreme wave conditions on U.S. coasts

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ABSTRACT

The Coastal Data Information Program (CDIP) maintains wave gauge stations for continuous coverage, with precision instruments and dedicated telemetry and dissemination infrastructure. Decades of this persistent, quality-controlled wave monitoring effort has provided the data required to generate metrics for wave climate at coastal locations across the United States and identify and characterize extreme wave events. During the extremely active 2020 North Atlantic hurricane season, the CDIP East Coast array recorded significantly elevated wave conditions generated by no fewer than 15 named storms. In California, meanwhile, long-term monitoring stations have measured new all-time maximum wave heights during recent storm events. Complete quality-controlled directional spectra and displacement data sets, as well as sea surface temperature and surface current data from the wave buoys, are publicly available at http://cdip.ucsd.edu.

KEYWORDS: Wave measurement, hurricane waves, extreme waves.

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The Coastal Data Information Program (CDIP) is an operational wave monitoring and prediction program based at Scripps Institution of Oceanography, part of the University of California, San Diego. Primarily funded by the U.S. Army Corps of Engineers (USACE), CDIP maintains an array of moored Datawell Waverider directional wave buoys in U.S. and territorial waters. Many of the stations analyzed in this report are cost-shared with partners: the California State Parks Division of Boating and Waterways, the U.S. Navy, NASA, and the National Oceanic Atmospheric Administration's U.S. Integrated Ocean Observing System (NOAA IOOS) Regional Associations.

Established in 1975, with adoption of directional Waveriders in the 1990s, and growth of the East Coast array starting in the 2000s, CDIP now curates decades of continuous intercomparable high-precision quality-controlled directional spectral data, and raw displacement-path wave data, from scores of real-time and historic monitoring stations at cdip.ucsd.edu and thredds.cdip.ucsd.edu, and redundant archives are maintained with the NOAA National Centers for Environmental Information (NCEI). Buoy data are telemetered every 30 minutes via the Iridium network, with real time call success rates >99% common. Real time records are disseminated via NOAA National Data Buoy Center (NDBC), as well as PORTS® under a memorandum of agreement. Any data records lost due to real-time communications issues are filled in from buoy internal memory following instrument recovery, every 1.5-3 years. Using calibrated precision instrumentation, leveraging cloud computing resources (Behrens *et al.* 2020), and employing rigorous QA/QC,[1] results in robust, high-quality data products (Behrens *et al.* 2019). The CDIP data record is a unique resource in the waves research community and serves as an underpinning reference data set for a steady stream of reports on wave climate (e.g. Seymour 2011; Erikson *et al.* 2018; Li and Huang 2020; Häfner *et al.* 2020) and wave energy (e.g. Lenee-Bluhm *et al.* 2011; Korde 2019; Desouky and Abdelkhalik 2019; Subramanian *et al.* 2018) as well as a wider swath of oceanographic and fisheries research.

1) U.S. Integrated Ocean Observing System, 2019. *Manual for Real-Time Quality Control of In Situ Surface Wave Data Version 2.1: A Guide to Quality Control and Quality Assurance of In Situ Surface Wave Observations*. 70 pp. https://doi.org/10.25923/7yc5-vs69.

2020 NORTH ATLANTIC STORM SEASON

The CDIP array has collected detailed information about recent active North Atlantic storm seasons (e.g. Behrens *et al.* 2018). The 2020 season was the most active on record,[2] with 30 named storms, 13 of which were hurricanes. Figure 1 and Table 1 provide an overview of the data set collected by the CDIP array during the 2020 North Atlantic storm season. This includes, at minimum, 95 distinct buoy records of elevated storm wave conditions, consisting of tens of thousands of hours of buoy displacement time series and directional spectral data. For all of these stations and storms, complete, quality-controlled data regarding wave period, direction, and multi-modal complexity are freely available.

In total, moored buoys at 24 stations measured significant wave height Hs, a common measure of wave intensity, of at least 2.5 m during the arrival of waves generated by Cristobol, Fay, Hanna, Isaias, Laura, Marco, Paulette, Sally, Teddy, Beta, Gamma, Delta, Epsilon, Zeta, and Eta. CDIP 240 Thimble Shoal, VA, wave height limited at only 8 m water depth at a location inside the mouth of Chesapeake Bay, was included in Table 1 due to the substantial waves observed during Isaias.

Along the east coast, Hurricane Isaias was a major wave event, and set the season's one new long-term wave height

2) NOAA NCEI. "North Atlantic hurricane Season Shatters Records." (17 December 2020). Retrieved 29 March from https://www.ncei.noaa.gov/news/2020-north-atlantic-hurricane-season-shatters-records.

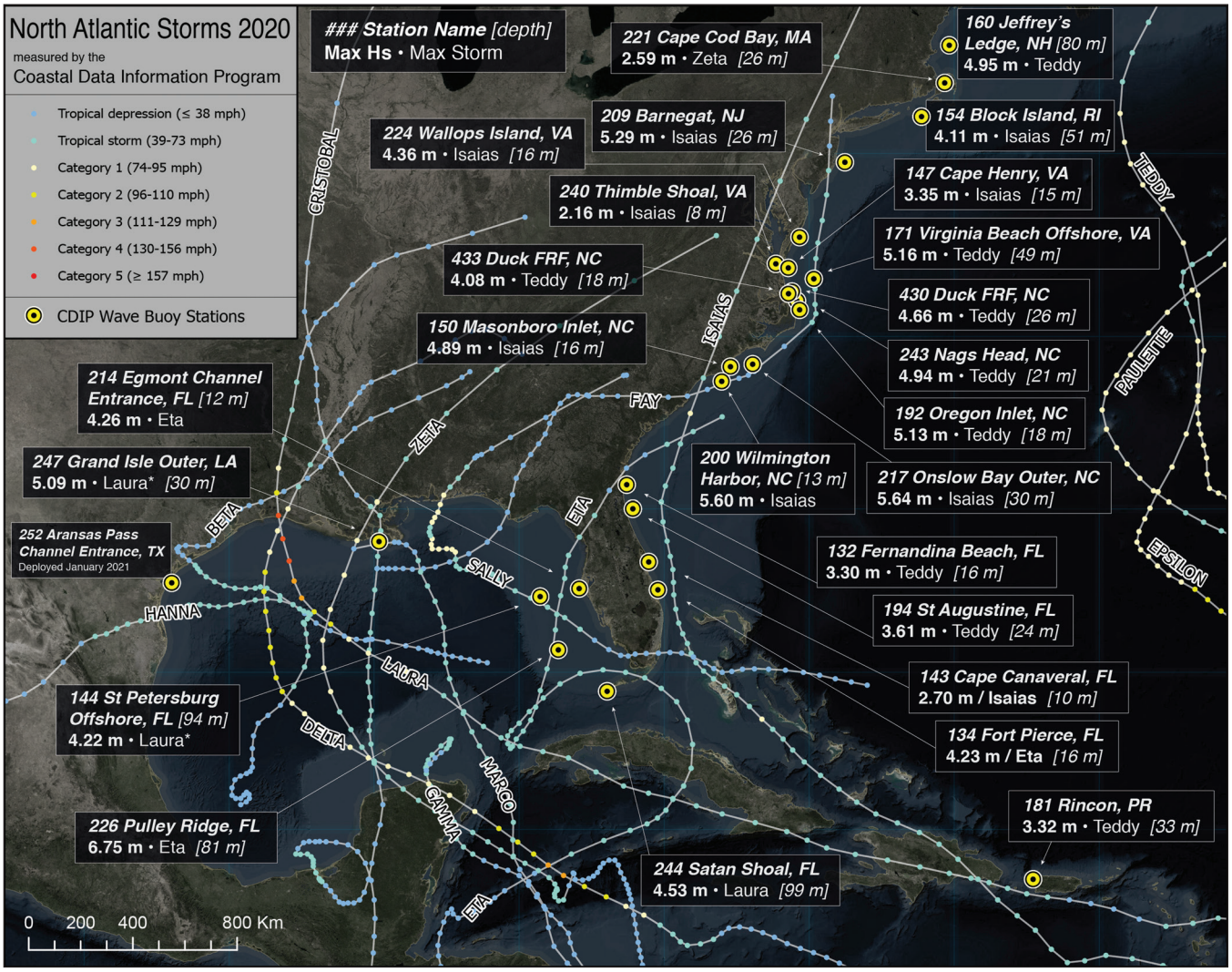

Figure 1. Map of CDIP moored directional wave buoy monitoring stations, January 2021, and the named storms of the 2020 North Atlantic hurricane season that generated waves measured by the array reaching Hs ≥ 2.5 m. For each station, maximum Hs measured during the season, and the related storm, are indicated, as is the station water depth. Storm track information from NOAA. (*Stations 144 and 247 had data gaps, see main text.)

record for the array, at CDIP 200 Wilmington Harbor, NC, which has been instrumented through all storm seasons since 2013. Hurricane Teddy, which formed at the peak of cyclonic activity, produced the most energetic waves of the season as measured by several buoys from the Caribbean to New England. The remnants of both Sally and Zeta, after following recurvature paths through the Gulf of Mexico, created significant waves on the East Coast. In Florida, Hurricanes Laura and Eta were most significant in terms of coastal wave heights.

Twelve storms made U.S. landfall in 2020, a new record. Five of those occurred in Louisiana, the most for any state in a season. CDIP established station 247 Grand Isle Outer, LA, in January 2020 and, despite periodic data outages caused by mooring damage, large storm waves were successfully measured there from Cristobol, Laura/Marco, Sally, Beta, and Delta. The buoy was adrift during the passage of Zeta. The only other stations with outages were 144 St. Petersburg Offshore, FL, which suffered a mooring failure in late September, causing it to miss Gamma, Delta, Zeta, and Eta; and 132 Fernandina Beach, FL, which was off station briefly and missed Isaias. All other buoy mooring systems held station and returned high-quality wave data throughout the duration of the season.

EXTREME WAVES IN CALIFORNIA

CDIP's wave monitoring efforts began on the California coast, and the longest wave climatological records in the data set exist there. Measuring new extreme wave conditions at these stations after decades of monitoring represents a statistically significant contribution to the understanding of the most potentially forceful events that will occur in the region.

On 27 November 2019, a bomb cyclone of historically low pressure[3] made landfall near the California-Oregon border (Figure 2e). CDIP 094 Cape Mendocino, CA, located ~30 km southwest of the cape, water depth 345 m, was first instrumented with a directional Waverider in 1999, and then continually starting in January 2004. During this bomb cyclone (Figure 2), maximum Hs at CDIP 094 reached 13.14 m, with period of peak energy Tp = 15.4 s and average period Ta = 12.8 s. This event set the all-time record for wave height measured by a coastal buoy in the CDIP array. (For perspective, the second largest wave event ever recorded at CDIP 094 was Hs = 10.86 m, nearly 20% smaller.) From

3) Duginski, P. 6 December 2019. "A record 75-foot wave off California coast was produced by big storm." *Los Angeles Times*.

Table 1.

CDIP moored directional wave buoy monitoring stations exposed to named storms, and the timing and bulk parameter details of the largest waves measured at each station as a result of the 2020 North Atlantic hurricane season: significant wave height Hs, period of peak energy Tp, average period Ta, and direction at peak energy Dp. The storm associated with those conditions is indicated, as are all storms that generated significantly elevated waves at that station, defined here as Hs ≥ 2.5 m (§Hs ≥ 2.0 m at station 240, see main text), from the list: Cristobol, Fay, Hanna, Isaias, Laura, Marco, Paulette, Sally, Teddy, Beta, Gamma, Delta, Epsilon, Zeta, and Eta. (*Stations 144 and 247 had data gaps, see main text. †World Meteorological Organization)

Station name	CDIP #	WMO † ID	Depth (m)	Date Time (UTC)	Max Hs (m)	Tp (s)	Ta (s)	Dp (°)	Storm of max Hs	Significant storm waves
Rincon, PR	181	41115	33	2020-09-24 5:00	3.32	13.33	11.38	006	Teddy	T
Grand Isle Outer, LA *	247	42093	30	2020-08-26 18:30	5.09	11.11	8.43	166	Laura/ Marco*	C, L/M, B, D*
Satan Shoal, FL	244	42095	99	2020-08-24 20:30	4.53	10.00	7.49	122	Laura/ Marco	L/M, ETA
Pulley Ridge, FL	226	42097	81	2020-11-11 11:00	6.75	9.88	8.50	163	Eta	H, L/M, S, G, D, Eta
St. Petersburg Offshore, FL*	144	42099	94	2020-08-26 1:30	4.22	11.76	8.98	197	Laura/ Marco*	L/M, S, B*
Egmont Channel Entrance, FL	214	42098	12	2020-11-12 0:00	4.26	9.09	6.84	213	Eta	S, Eta
Fort Pierce, FL	134	41114	16	2020-11-09 6:30	4.23	11.11	7.60	076	Eta	I, T, Eta
Cape Canaveral Nearshore, FL	143	41113	10	2020-08-02 19:30	2.70	9.88	7.23	112	Isaias	I, L, T, Eta
St. Augustine, FL	194	41117	24	2020-09-21 3:30	3.61	7.69	6.71	053	Teddy	I, T, Eta
Fernandina Beach, FL	132	41112	16	2020-09-21 3:00	3.30	8.00	6.47	063	Teddy	T, H
Wilmington Harbor, NC	200	41108	13	2020-08-04 2:30	5.60	12.5	9.33	177	Isaias	I, S, Z
Masonboro Inlet, NC	150	41110	16	2020-08-04 3:41	4.89	11.11	7.67	158	Isaias	I
Onslow Bay outer, NC	217	41159	30	2020-08-04 4:00	5.64	9.88	8.33	166	Isaias	I, S,T, Z, Eta
Oregon Inlet, NC	192	44095	18	2020-09-23 8:00	5.13	16.67	13.29	078	Teddy	I, S, T, Z
Nags Head, NC	243	44086	21	2020-09-23 6:17	4.94	16.67	12.35	075	Teddy	F, I, P, S, T, Z, Eta
Duck FRF 17m, NC	433	44056	18	2020-09-22 12:30	4.08	14.29	9.80	083	Teddy	I, S, T
Duck FRF 26m, NC	430	44100	26	2020-09-22 12:30	4.66	13.33	9.92	093	Teddy	I, P, S, T, Z
Virginia Beach Offshore, VA	171	44088	49	2020-09-21 23:30	5.16	13.33	8.86	097	Teddy	F, I, P, S, T, Epsilon, Z
Cape Henry, VA	147	44099	15	2020-08-04 10:30	3.35	7.69	6.01	147	Isaias	I, S, T
Thimble Shoal, VA§	240	44087	8	2020-08-04 11:00	2.16	4.35	4.40	156	Isaias	I§
Wallops Island, VA	224	44089	16	2020-08-04 13:00	4.36	9.88	7.15	144	Isaias	I, T, Z
Barnegat, NJ	209	44091	26	2020-08-04 17:30	5.29	9.88	7.76	167	Isaias	F, I, P, S, T, Z
Block Island, RI	154	44097	51	2020-08-04 23:30	4.11	9.09	7.22	200	Isaias	F, I, T, Z
Cape Cod Bay, MA	221	44090	26	2020-10-30 9:31	2.59	8.33	5.69	000	Zeta	Z
Jeffreys Ledge, NH	160	44098	80	2020-09-23 1:09	4.95	15.38	10.34	109	Teddy	I, P, S, T, Epsilon, Z

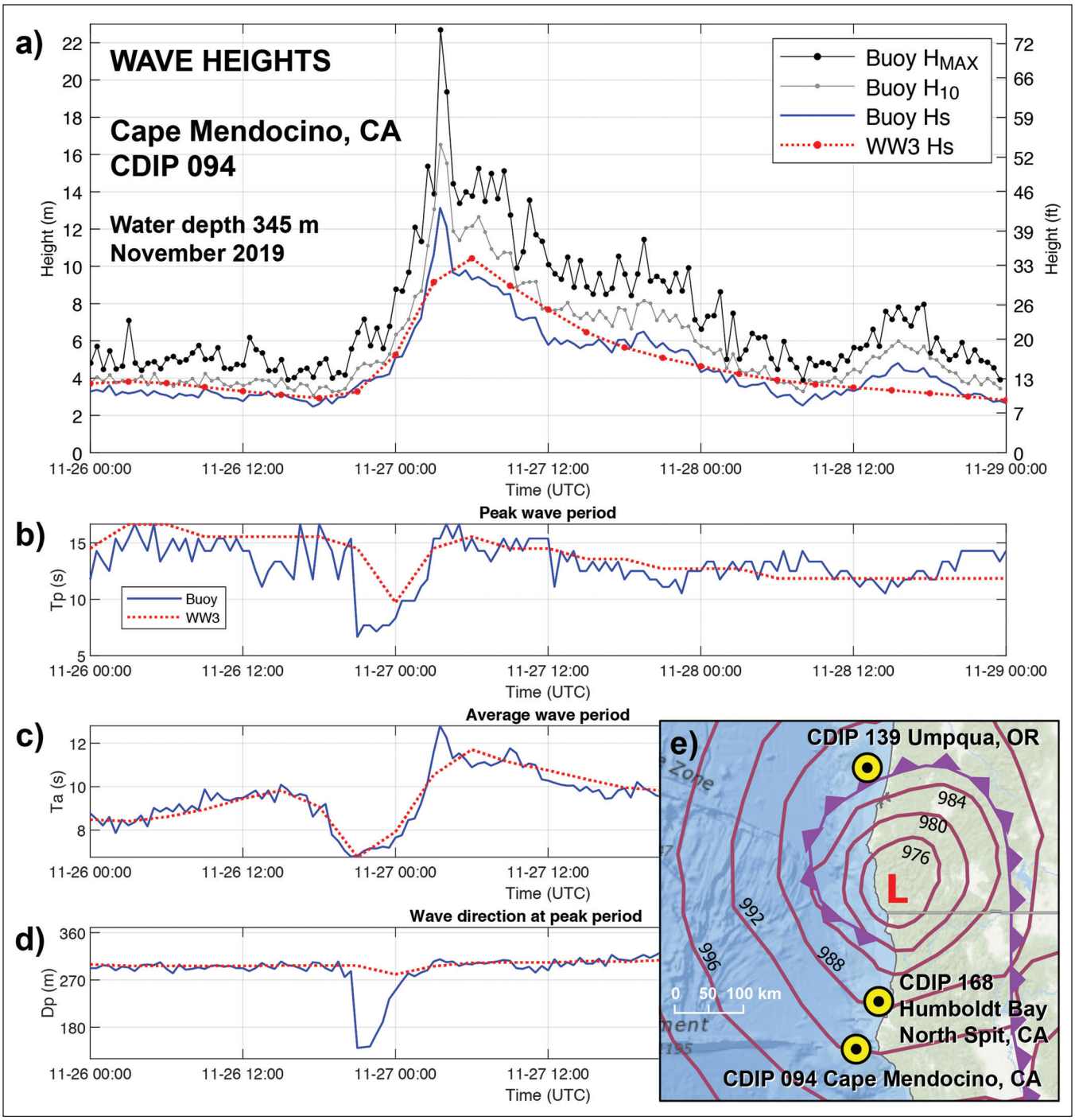

Figure 2. Directional wave conditions at CDIP 094 Cape Mendocino, CA, during the bomb cyclone of 27 November 2019, from a moored Waverider, with a time step of 30 minutes, and from NOAA's operational WaveWatchIII, with a time step of 3 hours (a-d). Station locations are shown (e) with the NOAA synoptic weather chart from 0300 UTC 27 November 2019 showing surface pressure in hPa. Wave height (a) is computed as H_{MAX}, the largest individual wave, and H_{10}, the average of the largest 10% of waves, from all trough-to-crest waves in the vertical displacement time series, and significant wave height Hs. With the exception of the peak, the model characterization of the bulk wave parameters of the storm waves was reasonably skillful.

the displacement time series, the largest individual wave had a trough-to-crest heave of 22.69 m, and at a factor of 1.73 times the Hs, it fits comfortably within the statistically expected range of wave heights for the analysis time interval. Station CDIP 166 Ocean Station Papa, in the abyssal Pacific Ocean 1,350 km west of Vancouver Island, maintained in collaboration with University of Washington, is the only other CDIP station to record waves with a greater Hs, which has happened, to date, on three occasions across nearly 10 years of monitoring.

CDIP 168 Humboldt Bay North Spit, CA, 75 km north of CDIP 094, was also in the path of the bomb cyclone. Moored in 110 m water depth, the buoy recorded peak Hs = 11.47 m, Tp = 15.4 s, Ta = 11.9, simultaneous with the peak at CDIP 094. This was the greatest Hs at this station, which has continuous data from February 2010, and puts it third behind CDIP 094 and CDIP 036 Grays Harbor, WA, in the ranks of CDIP-measured coastal wave heights.

The statistically extreme waves occurred for ~90 minutes, at two stations. Such an event was too brief to be captured by NOAA's operational WaveWatch III model, with a forecast interval of three hours (Figure 2a). At the next stations up and down the coast, wave data from CDIP 139 Umpqua, OR (320 km north of CDIP 168), and CDIP 029 Pt. Reyes, CA (280 km south of CDIP 094) were typical for the season. These extreme waves were formed under captured fetch conditions, and then came ashore after dark, at low tide, along a largely uninhabited stretch of California's "Lost Coast."

Another long-term monitoring station to record a recent new extreme wave height is CDIP 092 San Pedro, CA, 10 km from the Port of Long Beach, 483 m water depth, with continuous data since February 1998. On 25 January 2021, during a storm with strong local winds, Hs reached 5.20 m, with Tp = 9.09 s and Ta = 7.73 s.

CONCLUSIONS

Achieving a useful and statistically significant understanding of the extremes in wave climate requires persistent, precise, and geographically widespread monitoring. CDIP's efforts in this domain are providing coastal engineers and mariners with necessary data for planning and decision making. CDIP continues to maintain a reliable and robust monitoring array through partnerships, innovation, and thorough QA/QC protocols.

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