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TECHNICAL COMMUNICATIONS

Low-Cost Pressure Gauges for Measuring Water Waves

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ABSTRACT

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Waves have profound effects on coastal geomorphology, but the understanding of wave climate effects on coastal ecology is limited due, in part, to the high cost of commercial wave gauges. High-cost gauges also limit the scope of coastal wave models and the ability of coastal land managers to design effective restoration, conservation and enhancement projects. To address these limitations, a low-cost do-it-yourself (DIY) wave gauge was constructed using commercial plumbing parts, a pressure sensor, an Arduino© microcontroller and adapted accessories. Details on gauge construction, coding and an instructional video tutorial are provided. Performance of the DIY gauge was determined by measuring the agreement of raw pressure data recorded by the DIY gauge to a comparable commercial gauge in both a laboratory wave channel study featuring a series of wave tests and in a complementary field test. Agreement of raw pressure data among gauges in the wave channel study was assessed using paired *t*-tests and by fitting linear models. Field test data agreement was assessed by comparing the total wave field energy recorded by each gauge and by fitting a linear model to recorded raw pressure data. Pressure data agreement between the gauges was excellent in all wave channel tests with mean differences between pressure readings consistently near zero and with 95% of all differences lying within ±63 Pascals (<1 cm static water depth), on average. The greatest variability between readings occurred within tests featuring high-frequency waves, mirroring results reported by others. Still, raw DIY wave gauge data explained, on average, 91% of the variance in raw commercial gauge data in wave channel tests. Field performance testing indicated similar gauge responses with 92% total wave energy agreement. Thus, the DIY wave gauge is a viable alternative to high-cost gauges that could improve the understanding and management of coastal environments.

ADDITIONAL INDEX WORDS: *Arduino, boat wake, DIY, coastal ecology, pressure sensor, wave gauge, water waves, wind waves.*

INTRODUCTION

Waves shape coastal environments (Sorenson, 2006) and are a major driver of erosion (Leonardi, Ganju, and Fagherazzi, 2016). However, the effects of wave climate on the ecology of coastal environments are not fully understood (Fulton, Bellwood, and Wainright, 2005; Roland and Douglass, 2005). Questions concerning the influence of waves on coastal ecology are especially relevant in areas experiencing rapid wave climate modification from boating activity (McConchie and Toleman, 2003) and climate change (Reguero, Losada, and Mendez, 2019). Assessing wave climate is typically achieved using one of two methods: wind–wave models or field measurement using gauges. Wind–wave models are relatively accessible and inexpensive but are not designed to account for boat wakes, which are the dominant contributor to wave energy in some coastal environments (*e.g.*, rivers; McConchie and Toleman, 2003) and are a prominent feature in most inshore coastal areas (*e.g.*, Bilkovic *et al*., 2019). Commercial wave gauges can account for both wind–waves and boat wake waves but are inaccessible to many researchers because of their high cost (Table 1). Even if researchers have access to commercial gauges, the high costs may still effectively limit inferences from wave climate studies due to cost-driven limits on spatial resolution. Low-cost wave gauges could allow more researchers to perform direct wave climate assessments and increase the spatial resolution of wave climate data, furthering the understanding of coastal ecology and improving coastal conservation, enhancement, and restoration projects.

To address this need, this paper explores the feasibility of constructing a do-it-yourself (DIY) wave gauge using low-cost materials (*e.g.*, Beddows and Mallon, 2018; Lockridge *et al*.,

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Table 1. *Commercial and DIY pressure gauge features and costs including sensor characteristics. The DIY gauge features a sensor with capabilities similar to those of commercial gauges but at a lower cost.*

Gauge	Water Level Sensor	Sensor Resolution (Pa)	Sensor Accuracy (% FS)	Sampling Frequency (output in Hz)	Cost (USD)
Nortek Aquadopp	pressure transducer	up to 1	0.5	1 to 2	12,000
RBR Solo^3 D	pressure transducer	up to 200	0.05	up to 32	3,000
DIY gauge	digital pressure	up to 20	14.3	up to 120	<300

2016; Mickley *et al.*, 2018; Miller, 2014) and assesses the gauge's performance by evaluating agreement between the DIY gauge and a commercial gauge in laboratory wave channel and field tests. Results from this study demonstrate that the DIY gauge is an excellent alternative to high-cost commercial wave gauges. Additionally, novice-level details on gauge development, coding instructions, and a discussion of gauge applications and wave data processing are provided.

METHODS

DIY gauge performance was evaluated using a complementary laboratory wave channel study and field performance test approach. Several environmental characteristics can alter wave characteristics in the field (Sorenson, 2006) and, thus, the expression of corresponding pressure signals. Therefore, a series of laboratory wave channel tests were first explored to evaluate agreement between the DIY and a commercial wave gauge. Gauge agreement was further evaluated during a 5-day field deployment.

DIY Wave Gauge Description

Construction of the DIY wave gauge seeks a balance between accessibility, utility, and practicality. Housing materials include those that are readily available at home improvement stores and high-performance electrical components that have many user-friendly features including easy assembly, user-friendly documentation, and open-source libraries (Supplementary Table A1). These features are described in more detail below. In addition, an instructional video detailing each step of gauge construction is provided along with a list of gauge housing materials and electronic components with links for purchasing and current (*i.e.* 2019) costs in Supplementary Appendix 2 and Supplementary Table A1.

Sensing Water Levels

Similar to comparable commercial gauges, the DIY gauge uses a pressure sensor to measure water levels indirectly by relating pressure to water depth (Table 1). The pressure sensor used in DIY gauges is the MS5803-14BA (SparkFun Electronics, Boulder, Colorado, U.S.A.) and features a piezo-resistive sensor and an integrated 24-bit analog-to-digital converter that is programmable to various sampling frequencies. Variations of this sensor have been used previously for wave (Herbert *et al.*, 2018; Miller, 2014), depth (Beddows and Mallon, 2018), and tide level measurements (Miller, 2014), but literature searches suggest that none have been evaluated for agreement with commercial gauges.

Logging Water Levels

The DIY wave gauge is built around the Arduino© hardware and open-source software platform, similar to other DIY scientific instruments (*e.g.*, Beddows and Mallon, 2018; Lockridge *et al.*, 2016). As such, it features several Arduino-based components to control reading and logging of sensor data through time, including an Arduino Uno microcontroller, a data logging shield (with a built-in, real time clock), a battery, and a power booster (Supplementary Table A1). Likewise, the software to control the sensing of water levels and writing of timestamped sensor data to the secure digital (SD) card was developed in the Arduino integrated development environment (IDE) and uses open-source libraries. As currently configured, the DIY gauge runs (sampling at 8 to 10 Hz continuously) for approximately 5.5 days on one 6600 mAh lithium ion battery. This sampling schedule and battery configuration favors event-based gauge deployment (*e.g.*, tropical storms, weekend boat traffic). However, the adaptable nature of the DIY wave gauge housing (discussed below) allows simple battery life extension by increasing the number of batteries or with coding adjustments (*e.g.*, burst sampling). Event-based code for the DIY wave gauge is available for download at the Mississippi State University Coastal Conservation and Restoration Program website (http://coastal.msstate.edu/waves).

DIY Wave Gauge Housing and Deployment

Pressure sensor-based gauges are deployed in the water with a waterproof housing necessary for all but the pressure-sensing element of the sensor. In comparison to commercial gauges

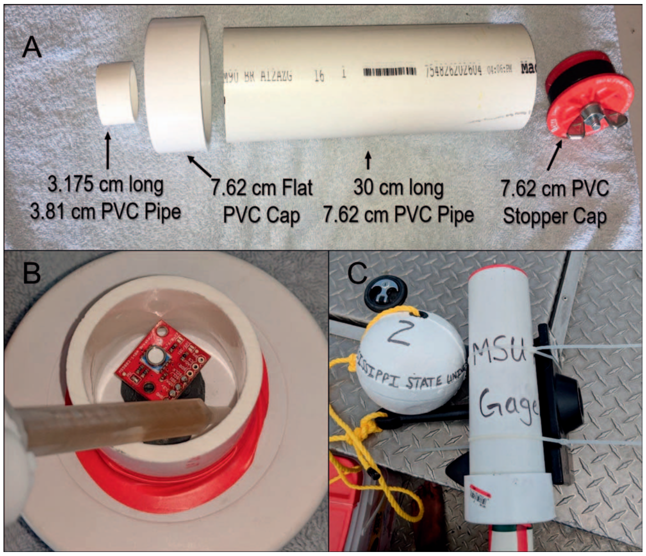

Figure 1. DIY wave gauge housing and deployment methods. (A) The DIY wave gauge is constructed from common PVC plumbing parts. (B) The pressure sensor is mounted within a smaller pipe on top of the flat PVC cap, which is waterproofed to the sensing element using epoxy. (C) The assembled gauge can be attached to an anchor fastened to a rope and buoy for easy deployment and retrieval in the field.

with specialized machined parts, DIY scientific instruments are typically constructed from nonspecialized common materials (Beddows and Mallon, 2018; Lockridge *et al*., 2016; Mickley *et al*., 2018; Miller, 2014). The DIY wave gauge housing is constructed similarly using common polyvinyl chloride (PVC) plumbing parts (Figure 1A). A standard 7.62 cm (3 inch) diameter pipe cut to 30 cm (~10 inches) length serves as the main body housing the sensitive electrical components (*i.e.* microcontroller, datalogger, battery, and powerbooster). A flat 7.62 cm diameter cap permanently seals one end of the main housing pipe and provides a base for sensor potting (*e.g.*, Beddows and Mallon, 2018) within a 3.81 cm (1.5 inch) diameter pipe cut to 3.175 cm (1.25 inch) length and glued approximately in the center of the larger cap using PVC cement (Oatey 31008 Heavy Duty Solvent Cement, Oatey, Cleveland, Ohio, U.S.A.). To pot the sensor (*e.g.*, Beddows and Mallon, 2018), a 1.27 cm (0.5 inch) diameter hole is drilled approximately in the center of the smaller pipe and through the flat cap, thus permitting the sensor wires to be fed to the microcontroller in the main housing pipe. The wired sensor is then set within the smaller pipe on the flat cap using epoxy putty (Rectorseal EP-200, CSW Industrials, Dallas, Texas, U.S.A.). Epoxy sealant (Loctite 237116 E-30CL Hysol Epoxy, Henkel AG & Co., Düsseldorf, Germany) is then poured evenly over the potted sensor so that sensor electronics are sealed while leaving the sensing element of the sensor exposed (Figure 1B). After the epoxy is fully cured (approximately 72 h), the flat cap is glued to the main housing pipe using PVC cement. A removable 7.62 cm cap (Oatey Gripper Mechanical Test Plug, Oatey) provides access to the battery and SD card within the main housing pipe while also providing a watertight seal (Figure 1A). Before deployment, desiccant packs and foam padding are added at either end of the main housing pipe to buffer the assembled gauge electronics. Constructed DIY wave gauges can be deployed in the field by securing them to anchors, such as boating anchors (Figure 1C), cinder blocks, *etc*., that rest on the sea floor or securing them to pilings. In total, the DIY gauge costs less than $300 USD, including housing and electrical components—an order of magnitude less than the closest comparable commercial gauge (Table 1). Details on gauge materials and building instructions, including videos, are available at the Mississippi State University Coastal Conservation and Restoration Program website (http://coastal.msstate.edu/waves; Supplementary Appendix 2, Table A1). Additional building instructions related to sensor testing and gauge coding are provided in Supplementary Appendix 3.

Laboratory and Field Testing

DIY wave gauge performance was evaluated in both laboratory and field tests. First, a series of wave tests were conducted in a laboratory wave channel study designed to minimize environmental error and to explore specific conditions known to increase error in pressure gauges (*i.e.* high-frequency waves; described below). Additionally, overall DIY gauge performance was evaluated in a 5-day field deployment test. Details of both tests, as well as special processing procedures for DIY wave gauge data and the statistical methodology used for comparisons are described below.

Wave Channel and Wave Test Description

A DIY and commercial wave gauge were programmed to sample at 8 Hz continuously and placed in a wave flume (17.5 m long × 1.5 m wide × 1 m deep; Armfield Limited) at the University of South Alabama (Mobile, Alabama, U.S.A.) for testing. The DIY gauge and the commercial pressure gauge (RBR Solo^3 D depth logger; hereafter "RBR") were attached to a 34 kg steel plate resting on the floor of the wave channel at a water depth of 60 cm. After the gauges were secure, a series of fifteen 90-second wave tests (five wave tests with three replications each; described below) were conducted using a wave generator (HR Wallingford) within the wave channel, with appropriate breaks in between tests to allow for water level settling.

The different wave tests included regular and irregular wave types and varied in wave characteristics (*i.e.* frequency and amplitude; Table 2). These tests were designed to create conditions that would maximize variability in pressure readings and to emulate real-world waves (*e.g.*, wind–waves and boat wakes). Tests 2 and 3 featured short-period (*i.e.* high frequency) waves known to increase variability in pressure signals due to pressure sensor limitations (*e.g.*, Lee and Wang, 1984) and the physical variability of wave phenomena (*e.g.*, Hoque and Aoki, 2006). Waves are rarely regular (*e.g.*, simple sine wave; Figure 2A) in the environment and are often irregular in nature (*i.e.* composite of multiple sine waves of varying frequency and amplitude). Therefore, in addition to tests featuring regular waves (Tests 1–4), Test 5 featured a wave spectra (Joint North Sea Wave Project) consisting of several irregular waves (Figure 2B).

Field Performance Test

The DIY and RBR gauges were deployed for 5 days (Thursday, August 30 to Tuesday, September 4, 2018) within Fowl River in Mobile County, Alabama. Wave climate in this mesohaline tributary of Mobile Bay is primarily the result of boating activity (Webb *et al*., 2018). Therefore, the timing (*i.e.* weekend deployment) and location (30°26′41.77″N, 88°07′40.79″W) were selected to maximize boat wake exposure (Webb *et al*., 2018). This reach of Fowl River is approximately 100 m wide with maximum depth less than 3 m and experiences a diurnal tidal cycle (max tidal range approximately 0.60 m). Black needle rush (*Juncus roemerianus*) marsh flanks both sides of the river channel.

Both gauges were deployed to a depth of 1 m at high tide within the subtidal mudflat and approximately 1 m from the marsh edge. The RBR was deployed by attaching the gauge to a PVC pipe driven into earth. The DIY gauge was deployed approximately 1 m from the RBR and parallel to the marsh edge by attaching the gauge to a 6.8 kg (15 lb) anchor (*e.g.*, Figure 1C).

In contrast to laboratory wave channel testing, the field setting is characterized by several potentially variable conditions that can increase the variability in gauge pressure readings that ultimately limit individual wave event comparisons. In particular, shoreline bathymetric (*i.e.* platform slope and elevation) and biological (*e.g.*, presence/absence of biota) features can vary substantially over relatively small distances in the field (Gomes *et al*., 2016), having various effects on wave characteristics (*e.g.*, height and breaking behavior; Sorenson, 2006) and subsequent pressure readings. In addition, signifi-

Table 2. *Laboratory wave channel test description and results. Wave test description includes information about wave frequency (F) and amplitude (A). Tests 2b, 2c, 3b, and 4a results were computed from gap-filled DIY gauge data. Test 5 uses JONSWAP wave spectra with* $H_s = 0.2$, $T_p = 2$, $\gamma = 3.3$.

Test Description				Linear Model				Analysis of Differences†			
Test	Rep	F (Hz)	A (m)	Intercept	Slope	R^2	P	Mean Difference	95% CI Lower (Pa)	95% CI Upper (Pa)	T-test P
1	a	0.5	0.08	0.000	1.08	0.99	0	−0.001	−63.4	63.1	0.93
1	b	0.5	0.08	0.004	1.08	0.98	0	0.003	−80.5	81.2	0.83
1	c	0.5	0.08	0.003	1.09	0.98	0	0.002	−73.2	73.7	0.87
2	a	0.99	0.08	0.000	0.95	0.84	0	0.000	−59.1	59.0	0.97
2	b	0.99	0.08	0.001	0.98	0.91	0	0.001	−44.9	45.2	0.87
2	c	0.99	0.08	0.001	0.93	0.83	0	0.001	−61.6	61.8	0.95
3	a	0.99	0.12	0.000	0.93	0.82	0	0.000	−81.8	81.8	0.99
3	b	0.99	0.12	0.000	0.81	0.69	0	0.000	−108.0	108.0	0.99
3	c	0.99	0.12	0.000	0.93	0.88	0	0.000	−67.1	67.1	0.99
4	a	0.75	0.12	0.003	0.94	0.92	0	0.004	−149.0	149.0	0.9
4	b	0.75	0.12	0.001	0.96	0.98	0	0.001	−70.6	70.7	0.97
4	c	0.75	0.12	−0.001	0.99	0.97	0	−0.001	−74.4	74.2	0.95
5	a	0.5	0.2	0.000	0.98	0.96	0	0.000	−108.0	108.0	0.997
5	b	0.5	0.2	−0.004	1.00	0.99	0	−0.004	−61.8	60.9	0.7
5	c	0.5	0.2	0.000	0.96	0.89	0	0.000	−166.0	166.0	0.99

† *CI = confidence interval*

cant temporal variability in the expression of different wave events is likely due to differences in gauge positioning (*i.e.* with respect to wave transmission) as boats pass by in different directions. This environmental and temporal variability in the field, coupled with the potential for further variability associated with wave–wave interactions (*e.g.*, wave phase shift) following the simultaneous advancement of two or more boats precludes individual wave event comparisons. However, wave energy density spectra describe the magnitude of wave energy as a function of wave frequency (Sorenson, 2006) and are thus unrelated to the timing of events. In addition, spectral analysis methods often incorporate filtering techniques to address

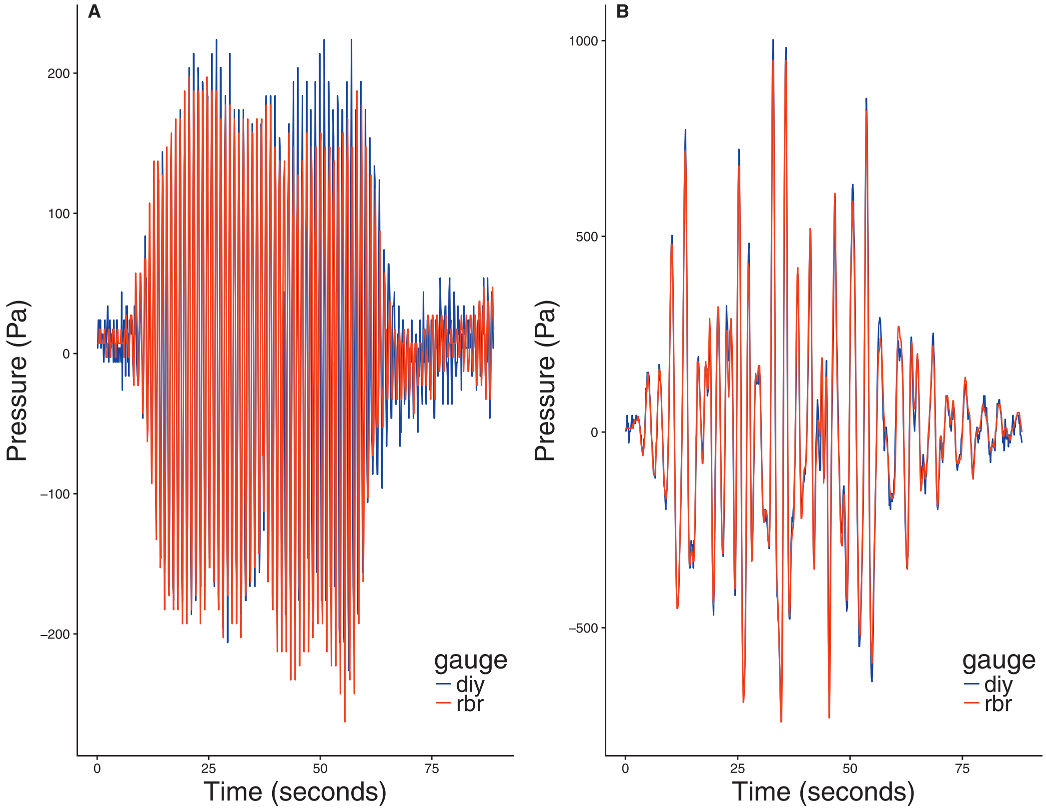

Figure 2. Overlaid DIY (blue) and RBR (red) pressure signals (Pa, y-axis) through time (seconds, x-axis). Panel (A) shows the signals from wave Test 3b, which features a regular wave (Table 2). Panel (B) shows signals from wave Test 5b, which features a series of irregular waves (Table 2). The DIY gauge is (A) within acceptable agreement at worst and (B) near 100% agreement at best.

environmental noise. These techniques were used to assess field test data agreement and are discussed further below.

Gap-Filling DIY Pressure Data

Initial processing of DIY pressure data indicated that a small portion (<1%) of data captures was missing (*i.e.* no pressure data were recorded; Supplementary Appendix 4). Therefore, a gap-filling routine was developed in MATLAB (2017) using linear interpolation to fill in missing data captures. This routine (available for download at http://coastal.msstate.edu/waves) was used to prepare field and laboratory data for statistical analyses in tests in which missing captures were identified (Table 2).

Statistical Analyses

Laboratory wave channel and field performance test data were assessed using different statistical procedures according to the objectives associated with each.

Following initial data processing (Supplementary Appendix 5), agreement for laboratory test data was determined by comparing paired raw pressure data from each gauge for each wave test. Overall agreement between raw pressure readings was assessed using paired *t*-tests and by examining differences along the range of pressure readings in each test, following Bland and Altman (1999). In addition, linear regression models were fit to paired raw data. Model coefficients were used to evaluate agreement further, while the coefficient of determination (R^2; hereafter, "model fit") was used to explore the conditions that maximized variability between gauge readings.

Field test data were compared using spectral analysis and linear regression techniques. Processed signals (Supplementary Appendix 5) were passed through fast Fourier transform sequences, which were then applied to periodograms to construct power spectral density (PSD) curves in MATLAB (2017). The total energy in the wave field (*i.e.* area under the PSD curve; m_0) contained in the DIY signal was assessed as a percentage of energy contained in the RBR signal to determine agreement as follows:

$$\text{Percentage agreement} = [m_{0(\text{DIY})}/m_{0(\text{RBR})}] \times 100 \qquad (1)$$

A linear regression model was fit to paired raw pressure data to further evaluate overall field raw data agreement.

All statistical analyses were performed in R (R Core Team, 2017). Figures were made using the ggplot2 (Wickham, 2011) package.

RESULTS

Raw DIY pressure data compared very favorably with that of the RBR in each of the wave channel tests (Table 2). Paired *t*-tests indicated no significant differences between gauge pressure readings in any of the tests ($P \geq 0.7$). Indeed, the mean difference between raw DIY and RBR pressure readings was consistently near zero (absolute value of mean difference $\leq$0.004). The 95% confidence intervals of mean differences across the range of pressure readings were variable, ranging from ±45 to ±166 Pa (Table 2, Supplementary Figures A1–A5), but on average 95% of observed differences fell within ±63 Pa (<1 cm static water depth). Linear model coefficients mirrored these results with slopes ranging from 0.81 to 1.08 but having intercepts consistently near zero (Table 2). However, model coefficients deviated from within ±0.1 of predicted values (*i.e.* slope = 1, intercept = 0) only once, in a test designed to maximize variability (*i.e.* Test 3b; slope = 0.81; Table 2). Likewise, model fit was variable as a function of testing design (Supplementary Figures A1–A5). As expected, model fit was poorest in Tests 2 and 3, ranging in R^2 values from 0.69 to 0.91 (Table 2). Model fit was $\geq$0.9 in all other test comparisons and was, on average, 0.91 throughout testing (Table 2).

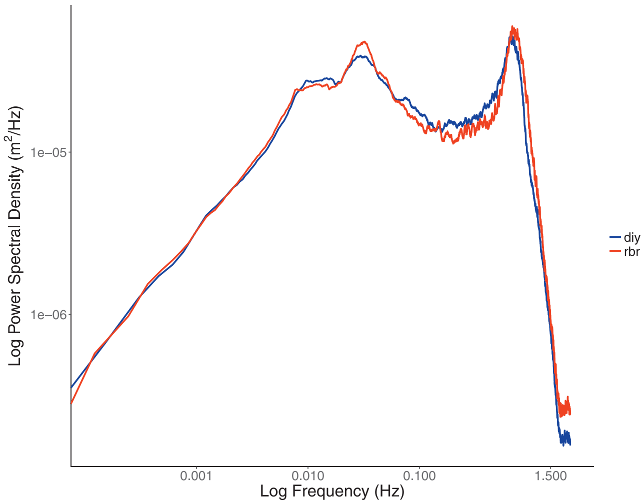

Figure 3. Overlaid DIY (blue) and RBR (red) power spectral density (PSD) curves constructed from field performance test data. The DIY PSD curve is very similar to that of the RBR across the different frequency bands (*x*-axis). The total area under each PSD (*i.e.* m_0) is also similar and overall wave field energy agreement is excellent (92%).

Field performance test data analyses mirrored laboratory wave channel test results. Wave energy density distribution was similar between the gauges (Figure 3), and total wave field energy agreement was excellent (92%). Model fit was also excellent ($R^2 = 0.997$) with model coefficients mirroring those found in the majority of wave channel tests (slope = 1, intercept = 0).

DISCUSSION

To expand on the performance of the DIY wave gauge, DIY and commercial gauge wave channel and field performance test data agreement are discussed in the context of pressure sensor limitations and agreement between other commercial pressure gauges reported elsewhere. This contextual description is followed by a discussion of DIY wave gauge applications, benefits, and details concerning data processing for wave climate inferences.

Agreement

This study explored the use of a low-cost DIY wave gauge in comparison with a commercial gauge with similar yet differing pressure-sensing technology (*e.g.*, sensor resolution and accuracy; Table 1). As such, some variability between DIY and RBR pressure gauge readings was expected, especially in wave channel tests exploring known pressure sensor limitations.

Indeed, some wave characteristics resulted in greater variability in gauge pressure readings (Table 2). However, variability was low in most tests ($\leq$10%), and differences between gauge readings were near zero with relatively little difference between readings across the range of pressure values ($\pm$63 Pa). Thus, overall agreement between the DIY and RBR gauges in all wave channel tests was excellent, including results from tests that most mimic real-world waves (Test 5; Figure 2B). Field performance testing provides further support as the DIY gauge tracked the RBR remarkably well (Supplementary Figure A1) and captured the range of frequency responses that comprise the total energy in the wave field as recorded by the RBR (Figure 3).

Increased variability between pressure readings was expected in wave channel Tests 2 and 3 due to the higher frequency waves examined in each of the tests. However, this increase in variability reflects a fundamental limitation of pressure sensors that is exacerbated by profound differences between gauges in electrical configuration (Lee and Wang, 1984) and shape (Bishop and Donelan, 1987). Discerning differences in the configuration and attributes of electrical components between the RBR and DIY gauges is difficult, if not impossible, without damaging the RBR. Still, it is reasonable to suspect a number of differences exist between the gauges that contribute to increasing signal noise at higher frequencies including differences in sensor type, power source, and numerical noise from analog-to-digital conversion (Lee and Wang, 1984). The most striking difference between the gauges is shape. Bishop and Donelan (1987) examined the potential effect of gauge shape on pressure signals by adding a sphere to the end of one pair of identical pressure gauges. They found this slight change in shape increased the error between the gauge signals by 5%. Considering the DIY wave gauge is three times as wide and twice as long as the RBR, these differences in shape are likely another source of error compounded by sensor limitations. Finally, differences in sensor attributes between the two gauges, including sensor resolution and accuracy differences (Table 1), are likely amplified during high-frequency wave events. While some reconfiguring of DIY electronics and/or technological advancement in the quality of components used in DIY gauges may improve agreement in these scenarios (*i.e.* high-frequency waves), several methods have been developed to deal with high-frequency signals. Under current conditions, DIY pressure data explained, on average, 86% of the variance in RBR pressure data within this frequency ($F = 0.99$ Hz), which is well within the range of interinstrument error reported elsewhere (80%; Bishop and Donelan, 1987; Esteva and Harris, 1970). This variability decreased with decreasing frequency in wave channel tests (Table 2), with similar results reported in the field performance test (Figure 3). Thus, the DIY gauge becomes more accurate within the frequency bands that contribute substantially to the energy density spectrum (Sorenson, 2006).

In summary, agreement between gauges was within acceptable ranges (Figure 2A) to near 100% (Figure 2B) in wave channel tests and excellent overall (92%) in the field performance test. Also, while some wave conditions created more variability between pressure gauges in wave channel tests, mean differences in all tests were essentially zero (Table 2). Therefore, the DIY gauge is a viable alternative to commercial wave gauges at a price point well below that of the closest comparable commercial gauges (Table 1).

Applications

This study explored a cost-effective tool that would allow researchers to increase the resolution and accuracy of wave climate models and/or pioneer new questions concerning the effects of wave climate on ecosystems. Beyond that, the DIY pressure gauge also has several practical uses, including enhanced environmental characterization for restoration and conservation planning by coastal land managers, consultants, contractors, and researchers.

In addition to practical applications, DIY gauges can be easily customized for specific needs. For example, with coding adjustments (*e.g.*, Beddows and Mallon, 2018), DIY wave gauges could be configured to sample periodically (*i.e.* short sampling intervals between longer sleep periods). This sampling adjustment would extend battery life significantly, allowing for longer deployments. In addition, since the gauge housing is also highly customizable, battery life could be extended by simply adding additional batteries. The DIY gauge could also be adapted for other water level monitoring applications (*e.g.*, river stage assessment, inundation, tide levels).

Finally, an underappreciated asset of low-cost gauges is that they are easily replaceable. Extreme weather events frequently have profound effects on ecosystem structure and function. However, deploying gauges during these events puts expensive equipment at risk. Using DIY gauges can greatly reduce financial risks to equipment associated with these events.

Data Processing for Wave Climate Inferences

Additional data processing and analysis is needed to make inferences from wave gauge data. These types of analyses were mostly avoided in this study because they are derivative and, thus, do not reflect actual instrument values necessary for agreement assessment (Bland and Altman, 1999). Nevertheless, extracting wave characteristics from field pressure data is necessary for wave climate assessment, for assessment of the effect of engineered structures on waves, and for calculating other wave-induced phenomena (*e.g.*, bed shear stress).

One approach to wave climate assessment takes a statistical approach to wave characteristics. In these statistical analyses, waves are identified from detrended signals (*e.g.*, mean water levels and/or tides removed) using a zero crossing method (*e.g.*, zero down-crossing; Forristall, 1978), and wave characteristics (*i.e.* wave height and period) are derived using linear wave theory approximations (Sorenson, 2006). Wave characteristics are then sorted in descending order for statistical analyses. Significant wave height ($H_{1/3}$ or sometimes H_s) is the most widely recognized statistic in these types of analyses, but it is simply the average of the top third of all wave heights in the record. Other wave statistics describe wave characteristics similarly by averaging within percentile ranges (*e.g.*, $H_{1/10}$ describes the average of the top one tenth of all wave heights in the record), while other statistics describe minimum and maximum values (*e.g.*, $T_{\max}$ describes the maximum wave period of all wave periods in the record). Wave statistics can be examined over the entire record or within discrete time intervals (*e.g.*, windows) throughout the entire record (*e.g.*, Roland and Douglass, 2005).

Another approach to wave climate characterization takes an approach similar to that described in the evaluation of field performance test data agreement (*i.e.* spectral analyses). In general, spectral analyses use a transformation (*e.g.*, fast Fourier transformation) to approximate a detrended signal, such as a record of water surface elevation data, as a summation of multiple sine waves characterized by differing wave amplitude and frequency. These transformed data are often used to determine the power spectral density contained in time series records as a function of wave frequency. This information can then be used to extract wave height and period parameters, since wave height squared is proportional to the energy contained in waves and wave period is inversely proportional to wave frequency. For example, spectrally significant wave height (H_{m0} or sometimes H_s) is a statistic derived from the total energy in the wave field (*i.e.* $\sim 4\sqrt{m_0}$).

Deriving these processing routines can be difficult for researchers without signal processing experience. Therefore, to enhance the application of the DIY wave gauge, links for basic processing routines using both methods are available for download at http://coastal.msstate.edu/waves. Directions for using scripts are provided in Supplementary Appendix 6.

CONCLUSIONS

The DIY wave gauge presented here is a cost-effective and highly customizable tool for measuring waves. Data accuracy is strong compared with a commercial gauge, and the gauge is easily constructed with little expertise. Several studies have examined the range of effects to ecosystems and the ecological significance of wave climate (*e.g.*, Fulton, Bellwood, and Wainright, 2005; Heuner *et al.*, 2015; Roland and Douglass, 2005; Rupprecht *et al.*, 2017). However, this research is limited in contrast to coastal engineering disciplines. DIY gauges can help to bridge this gap and to increase the interdisciplinary discussion necessary to further understand coastal ecology and to address pressing environmental issues like climate change.

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