Zong, Yaozhao; Cheng, Hao-Yuan; Chien, Hwa; Koppe, Bärbel

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Miniature Wave Buoy – Laboratory and Field Tests for Development of a Robust Low-Cost Measuring Technique

Y. Zhong, H.-Y. Cheng & H. Chien
Institute of Hydrological and Oceanic Sciences, National Central University, Taiwan

B. Koppe
Institute for Hydraulic and Coastal Engineering, Bremen University of Applied Sciences, Germany

Abstract: In order to fulfill the demand of real-time monitoring of meteorological-oceanic parameters for coastal and offshore applications, an easy-deployment and low-cost miniature wave buoy was developed, calibrated and tested. The calibration was carried out in the super wave tank at Tainan Hydraulic Labs (300 m long, 5 m in width and 5 m in depth). Comparisons between buoy and wave gauges were discussed in both frequency and temporal domain. Also, the miniature wave buoy was deployed in the coastal ocean of Taiwan for two months continuous observation. A comparison between this self-developed buoy and the traditional 2.5 m disc type large buoy was conducted. The results are highly consistent besides the wave direction parameter. Furthermore, sea surface Mean Square Slope (MSS) that measured by gyro, the inclination sensor of buoy hull, was calculated and regressed with in-situ wind speed U_{10}. The correlation coefficient between them could reach 0.81, indicating the capability of U_{10} measurement. It is also revealed from the watch-circle shape that tracked by GPS sensor, the tidal surface current could be inferred. Furthermore, a first buoy was deployed over a winter period of approx. six months off the Island Rügen showing the suitability of the technique also in cold environments of the German Baltic Sea.

Keywords: Miniature buoy; Wave measurement; Mean square slope; Surface Wind measurement

1 Introduction

In-situ meteorological-oceanic monitoring provides sea-truth data, which are essential for validation of remote-sensing technologies and numerical models as well as design of coastal structures and coastal hazard mitigation. In-situ observations in the coastal ocean are expensive, in terms of the instrumentation itself, deployment, maintenance and data communication. The costs for operational logistics can be 1-4 times the instrumental costs. For low-cost ocean wave measurements, Hirayama et al. (2004) developed the Ultra-Small-Directional-Wave-Buoy with the weight of 13 kg. In 2016, they developed the Mini-Buoy with a weight of 4 kg for easier operation in the field (Hirayama et al. 2016). The sizes of both types of buoys were greatly reduced and thus simplify the deployment, however, the power systems only allow them working for 8 to 20 hours measurement. In the present study, a more robust, functional miniature wave buoy with a power life span up to 6 months was developed. In this paper, the design, test, calibration and validation are introduced.

2 Data processing

2.1 Buoy structure

The structure of the present self-developed miniature wave buoy is shown in Fig. 1. From top to bottom it consists of an upper cover, a microprocessor for power control, data acquisition, online calculation and satellite data transmission, a sealing ring, a buoyancy adjusting ring, a stainless-steel dividing plate, a battery pack, and a lower cover. At the external bottom of a small ring offers the mooring line connection. The streamlined shape of the hull enhances the wave following ability of the buoy.

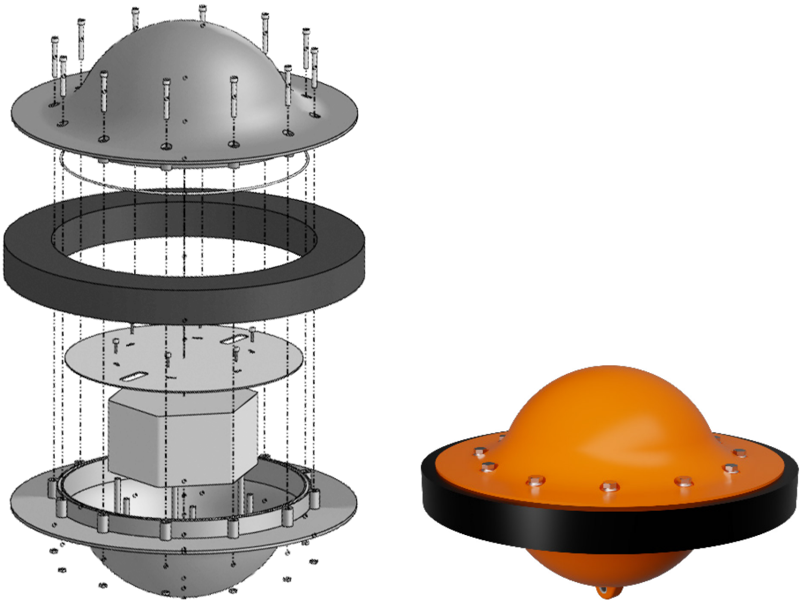

Fig. 1. Structure of the Miniature Wave Buoy.

2.2 *System architecture*

As revealed by Fig. 2, the microprocessor inside the buoy consists of the core (Atmega, 644PA/ 1284P), a micro-SD card, a real time clock and some extended channels for GPS, sensors and Iridium satellite communications. It can be powered by a battery or solar.

The wave height, period and wave direction are calculated online based on the 10-Hz raw data of pitch, roll, heading and accelerations in x, y and z directions, and then transmitted to the server databased via Iridium satellite communication once the wave parameters were calculated. All the raw data are recorded in the micro-SD card.

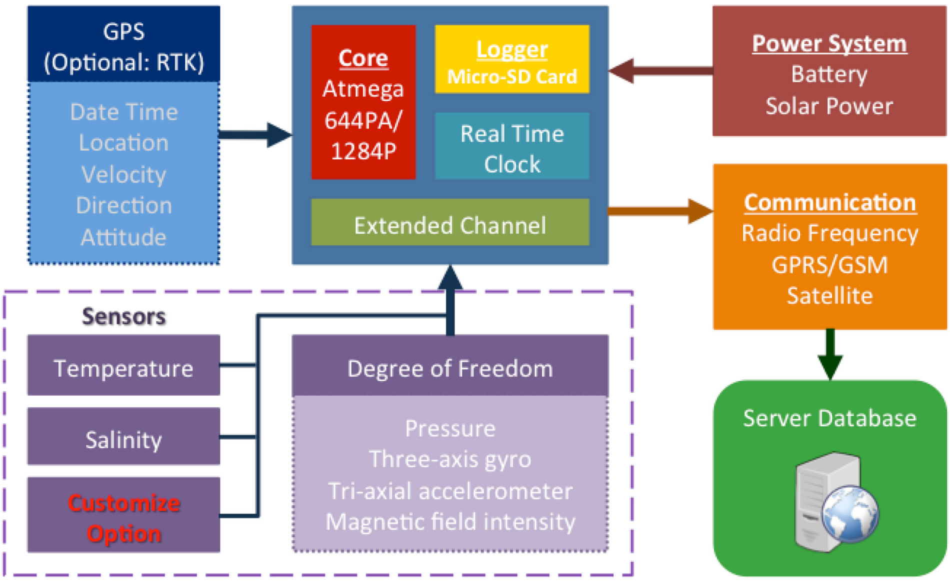

Fig. 2. System architecture.

2.3 *Data processing*

The significant wave height (H_s, unit: m) and mean period (T_m, unit: second) were calculated based on the following equations:

$$H_s = 3.8\sqrt{m_0} \tag{1}$$

$$T_m = \sqrt{\frac{m_0}{m_2}} \tag{2}$$

where m_0 is the average wave energy spectrum, m_2 is the second-order wave energy spectrum. They can be calculated as follows:

$$m_n = \int S_{\eta-a}(f) \cdot f^n df \tag{3}$$

where

$$S_{\eta-a}(f) = 2\frac{\Delta t}{L}|X_a|^2 \frac{1}{f^4} \tag{4}$$

where Δt = sampling interval, L = count of data, X_a = Discrete Fourier Transform of vertical acceleration. The vertical acceleration should be calibrated by pitch, roll and heading (Fig. 3).

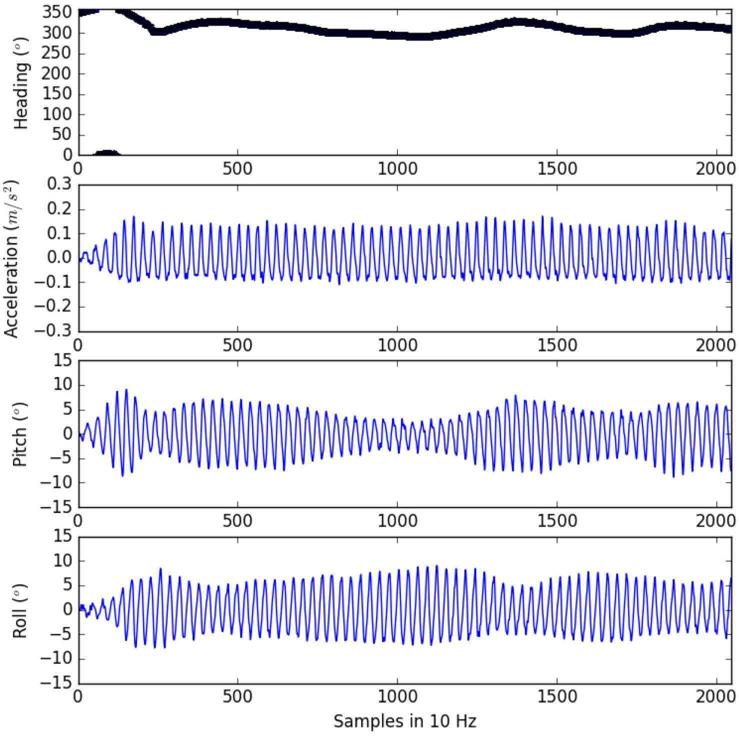

Fig. 3. An example of raw data from miniature wave buoy.

3 Wave Tank Calibration

3.1 *Experimental setup*

The test venue was the Tainan Hydraulics Laboratory of the National Cheng Kung University, Taiwan. For testing, the Super Wave Flume with the dimensions 300 m × 5 m × 5 m was used (Fig. 4). Both, regular and irregular wave tests have been executed on 2018-09-06. Details of wave making setting is shown in Tab. 1. Comparative measurements have been made with wave gauge (sampling rate is 20 Hz, measuring range of water level is 0.005 – 4.5 m, self-developed by the Tainan Hydraulics Laboratory) and Miniature Wave Buoy.

Fig. 4. Calibration testing of the miniature wave buoy in the Super Wave Flume of Tainan Hydraulics Laboratory.

Tab. 1. Experimental programme

Regular wave	0.1 m	0.2 m	0.4 m	0.5 m	0.6 m	0.8 m
1.5 sec.	Y	Y	Y	N	N	N
3.0 sec.	N	Y	Y	Y	Y	Y
5.0 sec.	N	N	Y	Y	Y	Y
7.0 sec.	Y	N	Y	Y	Y	N
Irregular wave*	0.1 m	0.3 m	0.4 m	0.5 m	0.6 m	
3.0 sec.	Y	Y	Y	Y	Y	
5.0 sec.	Y	Y	Y	Y	Y	
7.0 sec.	Y	Y	Y	Y	N	

* JONSWAP Spectrum, $\gamma = 3.3$.

3.2 Comparison between miniature wave buoy and wave gauge

Fig. 5 shows the comparison result between miniature wave buoy and wave gauge. The test results show that the self-developed buoy can measure the significant wave height, peak period of regular waves and mean period of irregular waves accurately.

The Pearson product-moment correlation coefficient was chosen as evaluation parameter:

$$r(A,B) = \frac{1}{N-1}\sum_{i=1}^{N}\left(\frac{A_i - \mu_A}{\sigma_A}\right)\left(\frac{B_i - \mu_B}{\sigma_B}\right) \tag{6}$$

The root mean square error (RMSE) is calculated as follow:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left[\frac{\sqrt{2}}{2}\left(A_i - B_i\right)\right]^2}{N}} \tag{7}$$

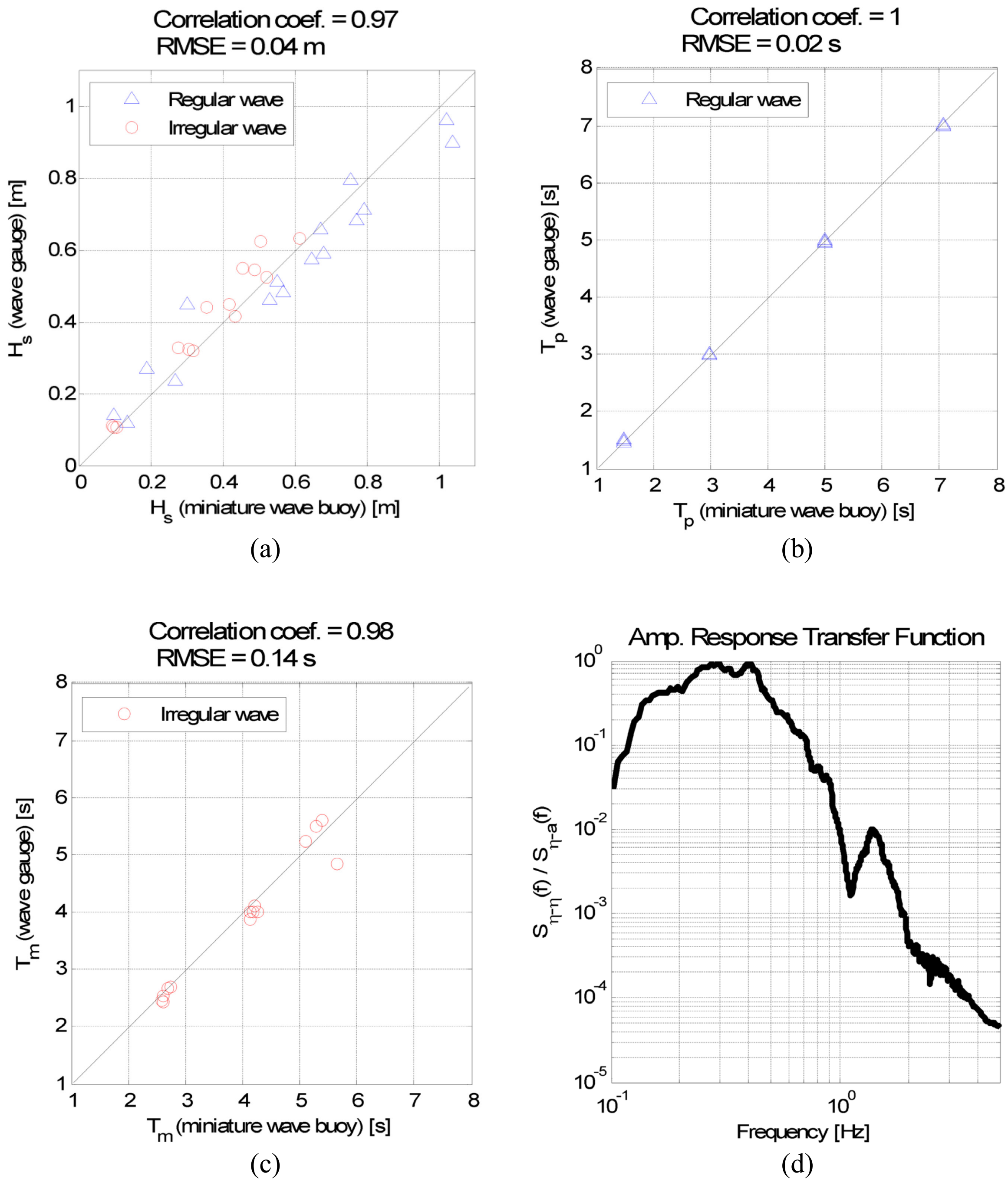

Fig. 5. Comparisons of significant wave height (a), peak period of regular waves, mean period of irregular waves between miniature wave buoy and wave gauge. (d) is the amplitude response transfer function between the $S_{\eta-\eta}\left(f\right)$ and $S_{\eta-a}\left(f\right)$.

4 Field experiments

4.1 Field comparison with 2.5-m buoy off the north-western coast of Taiwan

A field comparison with the traditional large buoy (developed by Coastal Ocean Monitoring Center, National Cheng Kung University) was conducted during the first season of 2019. The miniature wave buoy was deployed close to the large buoy located off Fu-Gui-Jiao at the north-western coast of Taiwan from January 19th to March 25th 2019.

The comparisons of significant wave height, mean period, peak period and wave direction are shown in Fig. 6, Fig. 7, Fig. 8 and Fig. 9, respectively. The results are highly consistent besides the wave direction parameter. There is a slight temporal delay between the 2.5-m buoy and the miniature wave buoy. It should be pointed out that the miniature wave buoy was moored at the northeast of 2.5-m buoy, 2.35 km away from it, and the frequently northeast waves (revealed by the blue dots in Fig. 9) arrived at the miniature wave buoy first, and then arrived at the 2.5-m buoy. In order to minimize the power consumption, the Miniature Wave Buoy enters the sleep state when it is not working, which cause the built-in compass to resume power supply at the beginning of each measurement. Thus, the compass starts to measure when it is not automatic calibrated, which reduces the accuracy of the direction measurement. The test of changing the power mode of the built-in compass is ongoing.

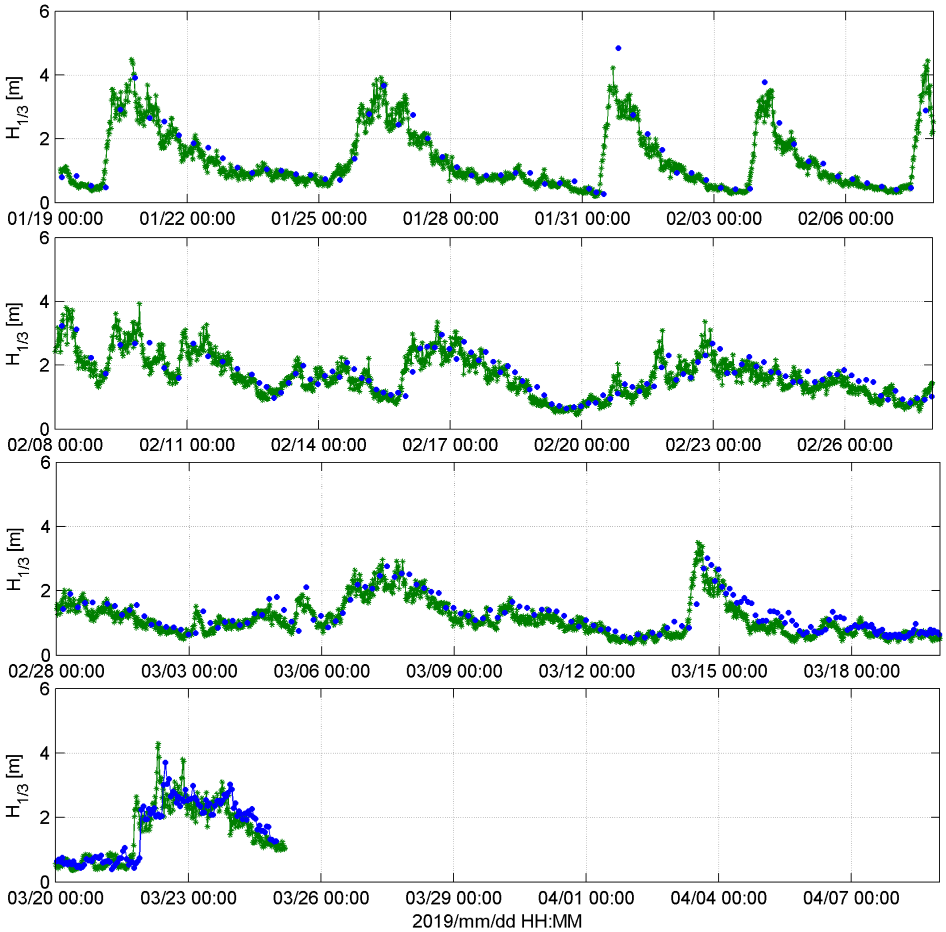

Fig. 6. Wave height comparison between miniature wave buoy (green dot) and 2.5-m buoy (blue dot).

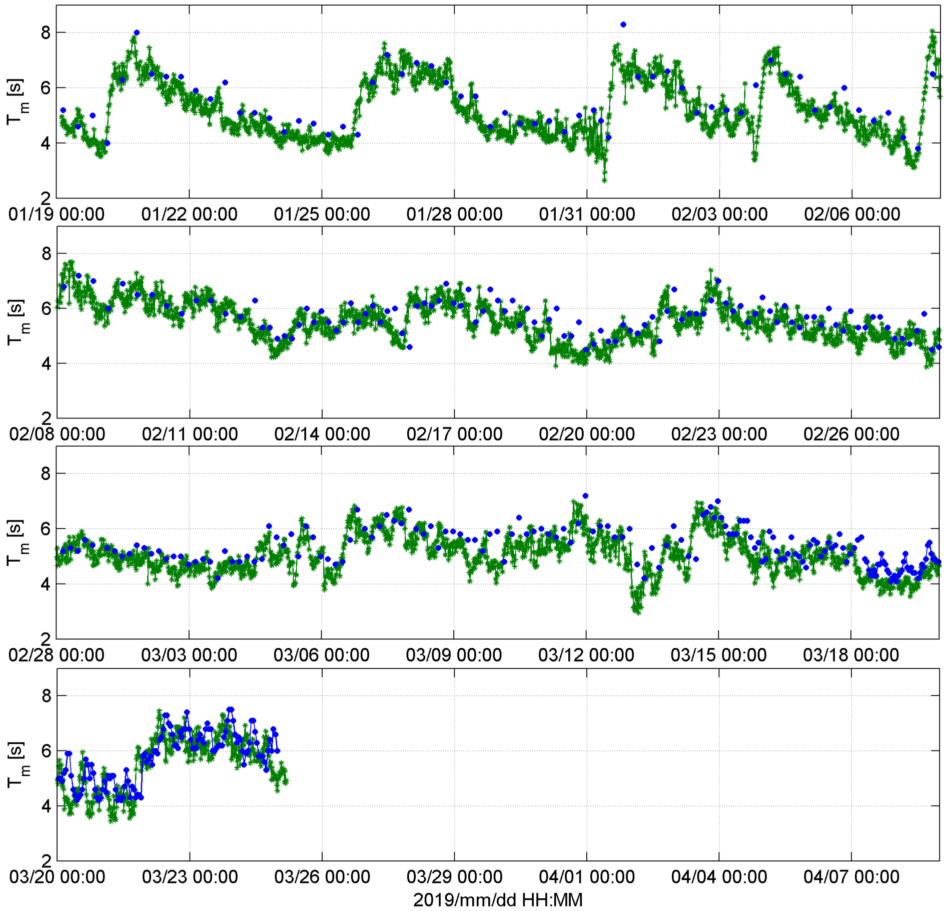

Fig. 7. Wave mean period comparison between miniature wave buoy (green dot) and 2.5-m buoy (blue dot).

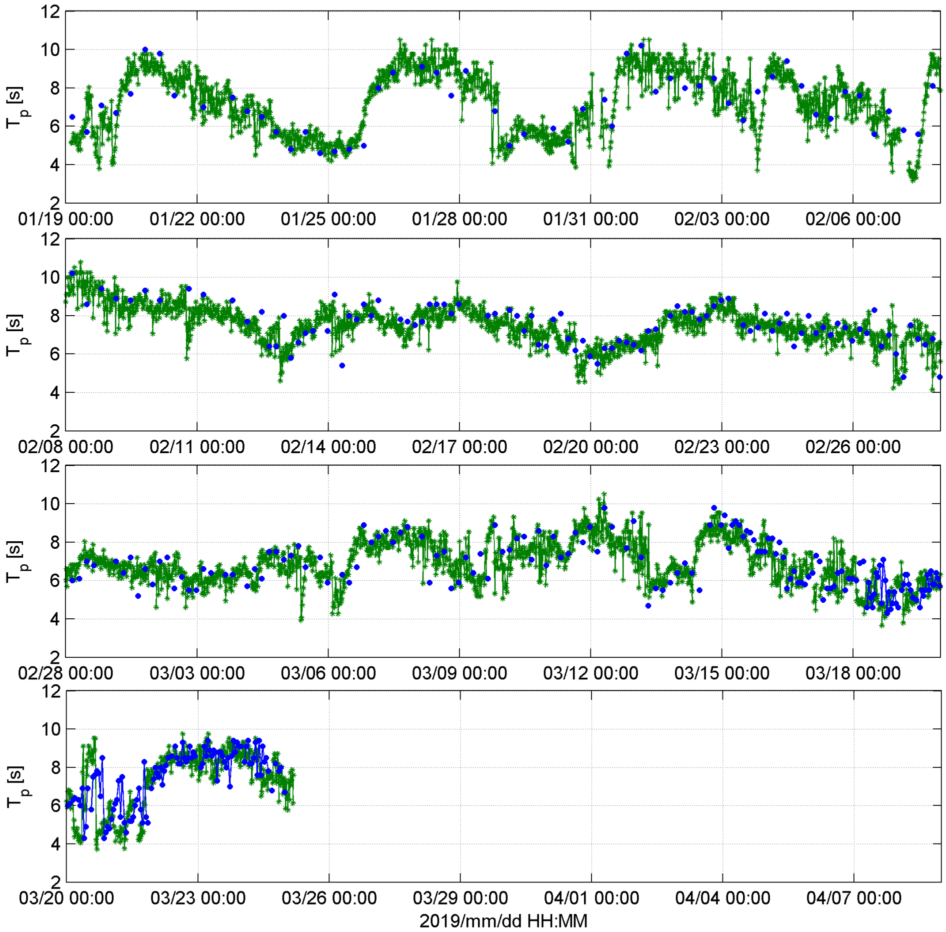

Fig. 8. Wave peak period comparison between miniature wave buoy (green dot) and 2.5-m buoy (blue dot).

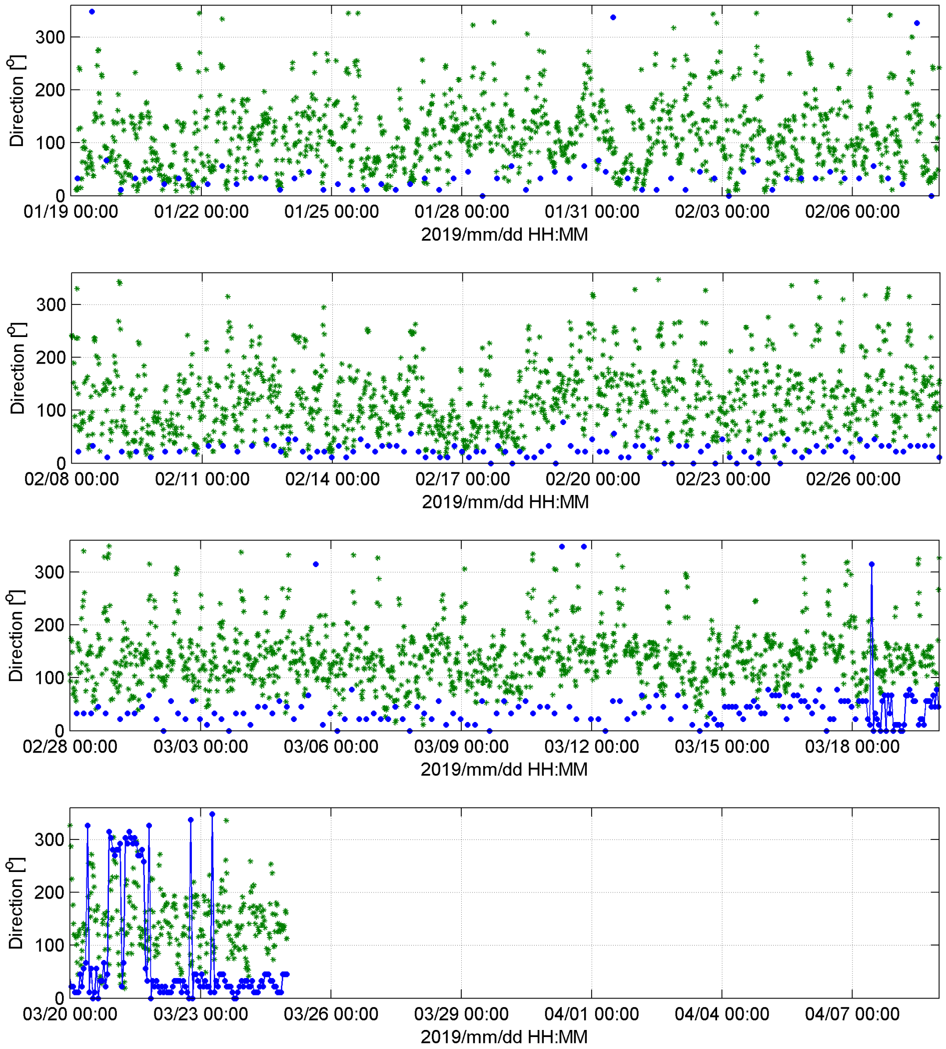

Fig. 9. Wave direction comparison between miniature wave buoy (green dot) and 2.5-m buoy (blue dot).

Beneath the measurement of wave data, the wind speed measurements also have been executed. As revealed by Fig. 10, the wind speed is significantly correlated (R = 0.81) with the mean square slope of sea surface. The relationship is consistent with Cox (1958) and Cox & Munk (1956).

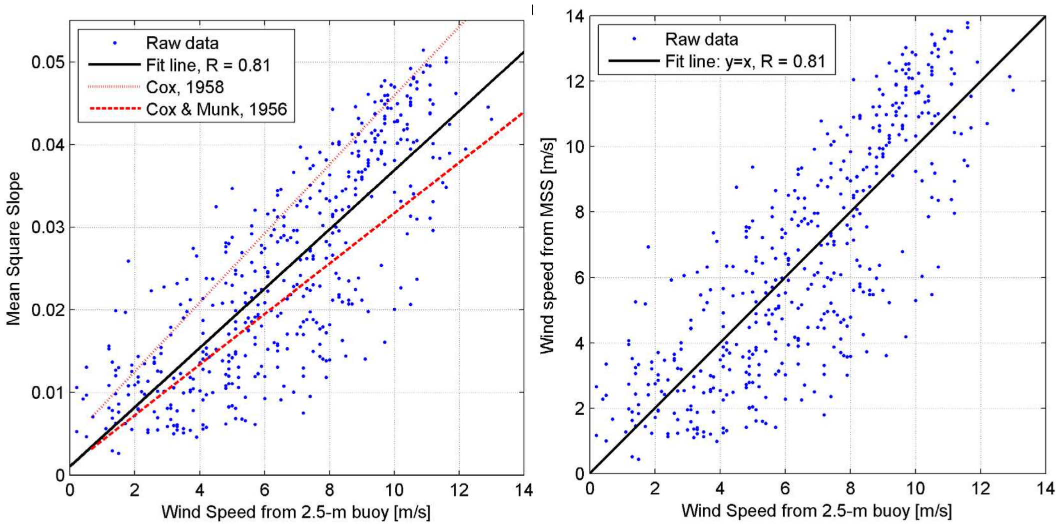

Fig. 10. Wind measurement based on mean square slope.

As the buoy floats on the sea surface and is anchored at a fixed point, the distribution of the buoy position reflects the effect of wave, currents, and wind. From the watch-circle shape (left panel of

Fig. 11) that tracked by GPS sensor, the tidal surface current could be inferred. The rotary spectrum of sea surface current is shown in the right panel of Fig. 11. Besides the M2 tidal constituents (12.46 h), several shallow water tidal constituents, like M4 (6.20 h), M6 (4.09 h), M8 (3.08 h), were revealed significantly by the rotary spectrum. The maximum amplitude of spectrum occurs at the frequency of M4 and M6 tidal constituents, which are approximately 5 times of that of M2.

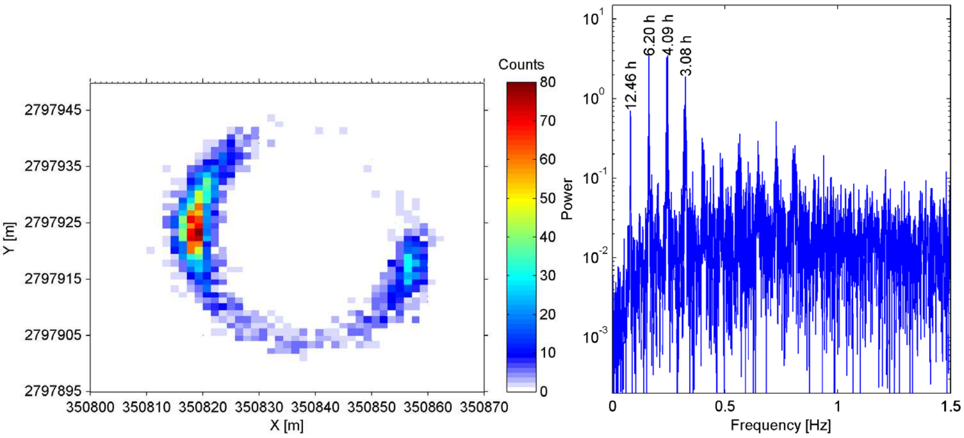

Fig. 11. Rotary spectrum of sea surface current measured by Miniature Wave Buoy.

4.2 Field measurements off the coast of the Island Rügen, Germany

In summer 2018, a collaboration project between National Central University (NCU) Taiwan and the Bremen City University of Applied Science (HSB) started using prototypes of directional wave buoys developed by NCU off the coast of the Island Ruegen at the German Baltic Sea coast in a water depth of 14 m (Fig. 12). The project is part of a feasibility study for the development of a leisure boat harbor in the district Prora of the Sea Resort Binz. A central issue is the impact assessment of the planned harbor entrance jetties on the sediment transport processes in the area. On November 1st 2018 the Miniature Wave boy was deployed using a rubber dinghy of the German Rescue Association DLRG. Measurements lasted until end of April 2019 and have been stopped due to low battery power, showing that a measuring period of almost six months is even possible in harsh winter conditions in the German Baltic Sea. An example of the preliminary wave parameter assessment of the data gained off the Island Rügen is shown in Fig. 13. Two storm events resulting in severe flooding events along the whole German Baltic Sea coast have been present on January 1st and January 9th 2019 showing also prominent significant wave heights of about 3 and 4 m. After replacement and retrieval of the buoy further data assessment will be conducted. It is planned to continue the wave measurements in the Prorer Wiek at least until spring 2020.

Fig. 12. Wave measurements with miniature wave buoy in the Prorer Wiek, Island of Ruegen, Germany.

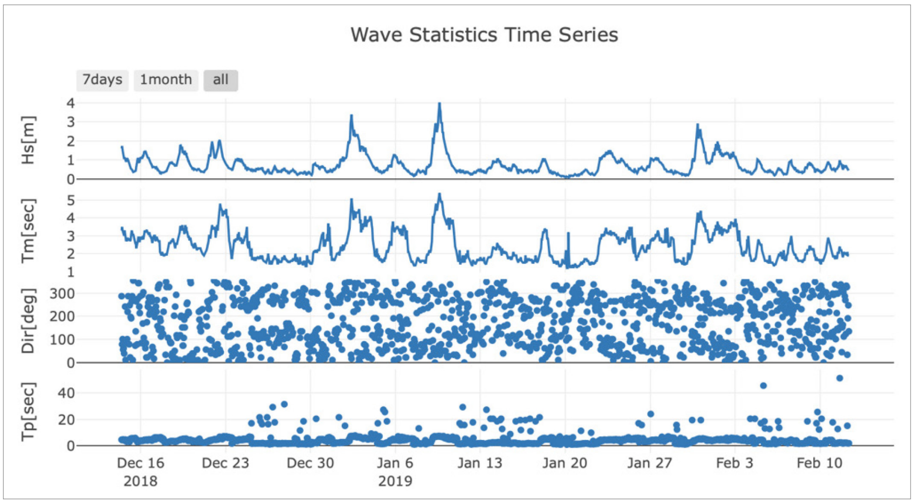

Fig. 13. Preliminary wave statistics of the Miniature Wave Buoy off the coast of the Island Rügen from 2018/12/15~2019/2/10.

5 Summary

Nearshore hydrodynamics, including longshore current, rip current and eddies in the coastal zones and estuaries are considered as the processes that shape the coast. The characteristics of nearshore hydrodynamic are dominated mainly by ocean waves and their breaking, also tidal current, wind driven current as well as riverine discharge plays a role. The processes can become more complex when interacting with shoaling bathymetry, coastline and artificial structures. The understanding of the nearshore hydrodynamics is challenging and yet essential for accurate prediction of coastal erosion and accretion and coastal hazard warning.

The National Central University (NCU) Taiwan developed a low-cost miniature wave buoy. In 2018 and 2019 calibration and field tests have been executed successfully in the Super Wave Flume of Tainan Hydraulics Laboratory and off the north-western coast of Taiwan. Additionally, field measurements have been started in November 2018 in the German Baltic Sea off the coast of the Island Rügen showing the suitability of the measuring technique for long-term measurements also in northern latitudes. The measurements in Germany will be continued until spring 2020.

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