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Development and Application of an Acoustic System for Harmful Algal Blooms (HABs, Red Tide) Detection using an Ultrasonic Digital Sensor

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Abstract – The overgrowth of phytoplankton leads to negative effects such as harmful algal blooms (HABs, also called red tides) in marine environments. The HAB species *Cochlodinium polykrikoides* (*C. polykrikoides*) appears frequently in Korea during summer. In this study, we developed a real-time acoustic detection and remote-control system to detect red tides using an ultrasonic digital sensor. In the laboratory, the acoustic signals increased as the number of cells increased. At the same time, for field application, we deployed the system near the southern coast of Korea, where red tides frequently occurred in summer seasons 2013–2015. The system developed here detected red tides *in situ*, with a good correlation between the acoustic signals and *C. polykrikoides* populations. These results suggest that it may be useful for early detection of red tides.

Keywords – harmful algal blooms, red tide, *Cochlodinium polykrikoides*, real-time acoustic detection system, ultrasonic digital sensor

1. Introduction

Harmful algal blooms (HABs, also called red tides) occur due to overgrowth of phytoplankton in marine environments (Kim et al. 2001; Jeong et al. 2011). HABs cause damage to aquaculture and fisheries as well as to marine ecosystems all over the world (Rhodes et al. 2001; Rabalais et al. 2009; Kudela and Gobler 2011). One dinoflagellate species responsible for red tides is *Cochlodinium polykrikoides* (*C. polykrikoides*) (Kim et al. 2001). In Korea, blooms of this species have occurred at irregular intervals since the 1990s (Jeong et al. 2011). Red tides were reported to cause about 76.4 million US dollars in aquaculture damage in 1995 and 24.7 million US dollars in such damage in 2013 along the southern and eastern coasts of Korea (Seo et al. 1998; NFRDI 2014).

In general, a red tide is classified or categorized in the precaution stage in Korea when the number of cells is 100 to 1,000 cells/mL, and it is considered to be in the warning stage when the number of cells is greater than 1,000 cells/mL (NFRDI 2014). *C. polykrikoides* exhibits little change in population density early in its occurrence. This red tide species is known to take about a week to proliferate from 170 cells/mL to 2,200 cells/mL during rapid multiplication (Seo et al. 1998).

Until now, studies on phytoplankton have been carried out by measuring photosynthesis, cell division, and the number of cells using a laboratory microscope (Ahn et al. 2005; Lim et al. 2007). To detect red tides in the ocean, ship-based visual observation is used most often, and cell populations are counted from sampled seawater using a microscope, whereas a fluorometer is used to measure photosynthesis (Lim et al. 2007). These processes carry high monetary and labor costs. The visual observation and counting method requires time-consuming analysis and can be conducted only during the daytime. *C. polykrikoides* is difficult to detect due to its rapid movement with currents and fast growth rate (Ahn et al. 2005). Recently, wide-area detection methods based on aerial or satellite observations have been used. Satellites are limited by low resolution because of the technical specification of a 500 × 500 m pixel, which leads to errors when red tide populations are small. These methods are also unable to detect red tides when the weather is cloudy

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(Ahn et al. 2005; Angles et al. 2008).

Acoustic investigations of red tide plankton have been carried out using ultrasound (Blanc et al. 1998). A frequency band below 1 MHz is primarily used for fisheries and zooplankton, but the acoustic characteristics of small phytoplankton have been insufficiently investigated (Holliday and Pieper 1980; Stanton et al. 1996; Blanc et al. 2000; Foote and Stanton 2000). Recently, phytoplankton measurement methods using ultrasound have also been proposed (Bok et al. 2010, 2013; Kim et al. 2010, 2017; Kang et al. 2013). Bok et al. (2010) and Kim et al. (2010) detected red tides using backscattered acoustic signals in the laboratory and in the southern coastal ocean of Korea. As another approach, acoustic characteristics from a scattering model were compared with measured backscattering strengths, based on a fluid-sphere scattering model (Kim et al. 2010). These studies focused on the possibility of the detection of phytoplankton using acoustic signals. To detect the red tide phenomenon, it is necessary to construct a system that can measure continuously in the ocean. In our previous study, conducted between 2008 and 2012, we developed and evaluated a red tide acoustic detection system in buoy, ship-based, and portable forms (Kang et al. 2013). However, these systems used an analog sensor type and were inaccurate because noise was not considered.

The objective of this study was to develop a real-time acoustic detection system for red tides using an ultrasonic digital sensor. Additionally, we developed remote-control and real-time monitoring techniques. The developed system minimized the system and electromagnetic noises by using a digital sensor, thereby improving the accuracy of the acoustic backscattering signals. We employed a remote control device for more efficient system management. To detect red tides, we evaluated this system in a laboratory and in the coastal ocean. We tested the effectiveness of a portable type system optimized for real-time detecting of HABs and to prevent damage to fish farms.

2. Materials and Methods

Acoustic characteristics and backscattering signals of *C. polykrikoides*

C. polykrikoides is one of the most common dinoflagellate species observed during summer in Korea. The species usually forms a chain with 1, 2 and 4 cells in the laboratory, and with up to 16 cells in the ocean (Matsuoka et al. 2008). From an acoustical perspective, the species such as phytoplankton are weak acoustic scatterers, with sound speeds and densities similar to seawater (Blanc et al. 2000). In general, the acoustic scattering region can be determined by the operating frequency (k) and radius of species size (a) (Medwin and Clay 1998). According to a previous study, the equivalent spherical radius of the species ranged between 12 μm for a cell and 30 μm for 16 cells of chain (Lim 2013). To study very small equivalent spherical radii, a transducer (A381S-SU, Olympus, Waltham, MA, USA) that is a commercial product was used with 3.5-MHz frequency in this study. Therefore, ka of the operating frequency and species size values are 0.1758 for 12 μm and 0.4396 for 30 μm. Consequently, *C. polykrikoides* is represented in the Rayleigh scattering region.

When Rayleigh scatterers of the same size are contained in a volume, the volume backscattering strength (S_v) was expressed by the total backscattering cross section, the radius of the spherical scatterer, the wave number, and the density and sound speed ratios (Clay and Medwin 1977; Johnson 1977). The volume backscattering strength was proportional to the number of cells, assuming that the Rayleigh scattering bodies were randomly distributed in seawater. However, the sound speed and density of *C. polykrikoides* are not easy to measure, and computing the theoretical S_v is complex (Bok et al. 2010). Thus, the relatively received level (RRL) is easy to compute the S_v.

The RRL was defined as the ratio of the received level from a scatterer and the reference level. Eq. (1) is defined by

$$\mathrm{RRL} = 20\log_{10}\frac{V_{s,bs}}{V_{s,ref}}, \tag{1}$$

where $V_{s,bs}$ and $V_{s,ref}$ are the root mean square (RMS) voltages of backscattered signals from a scatterer and a reference, respectively. In this study, we tried to measure received level due to red tide species, *C. polykrikoides*, for reference conditions. As a reference level, therefore, both methods were used in the laboratory and field measurements. Firstly, the reference level in the laboratory experiments was determined by the received level from measuring filtered seawater. On the other hand, the values in the field applications were determined from the received level measured under the no red tide condition in coastal oceans.

Composition of the acoustic detection system

We developed a portable type real-time acoustic detection system for red tides using ultrasound, as shown Fig. 1. The system consisted of a sensor and signal processing, network,

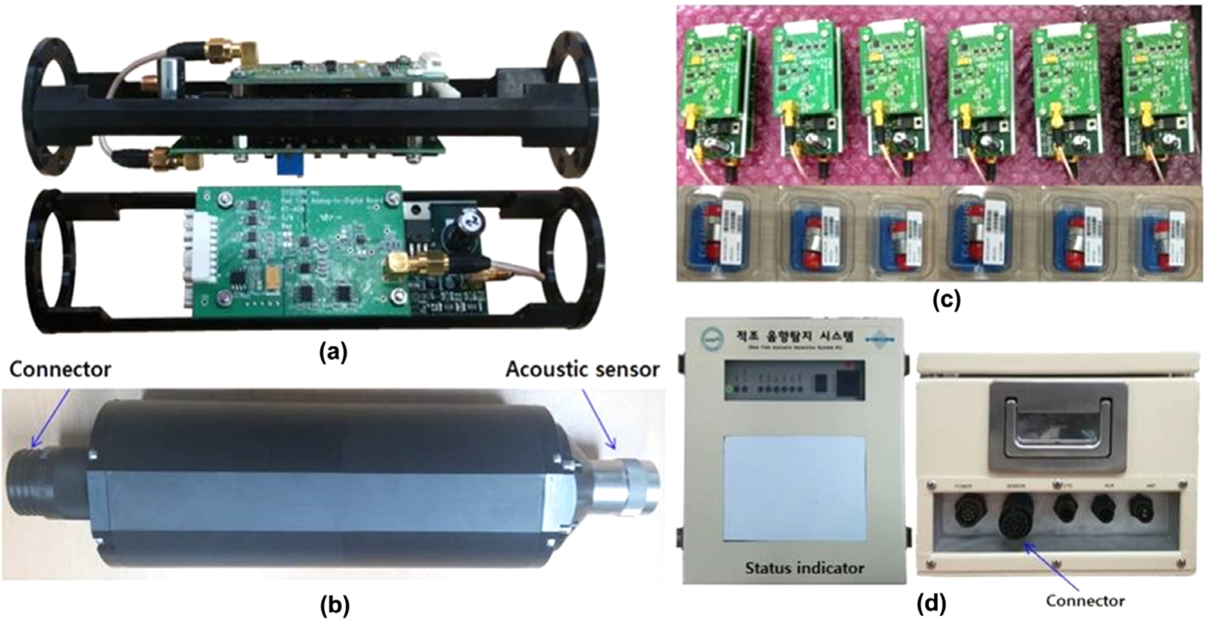

Fig. 1. Configuration of the real-time acoustic detection system for red tides. (a, b) Internal and external structures of the sensor component, (c) the pulser/receivers and the 3.5-MHz ultrasound transducers, and (d) the modular system

and power components. A single board technique was used to minimize noise, improving the accuracy of the received acoustic signal. For long-term operation in seawater, the surface material was acetal, which does not rust. The internal boards were flame retardant. Details of each component are provided below.

The transducer was a piezoelectric type employing the negative spike excitation method. Ultrasonic pulses were generated by applying a short-duration electrical signal to the pulser/receiver. In general, system noise increases as the distance between sensor and an analog-to-digital converter (ADC) increases. The received backscattering signals from the red tide phytoplankton are relatively weak in the seawater. The signals, therefore, have the potential to increase noise as analogue signals (or sensor) with a long cable used at high frequency. In order to minimize system noise during AD conversion, we applied a conceptual design with a digital sensor and finally integrated a built-in digital sensor with the ADC, pulser/receiver, and filter. From the sensor development, system noise significantly decreased and the built-in digital sensor was not limited by the acoustic sensor cable in seawater.

The filtered signal was converted into an enveloped signal using an envelope detector. The enveloped signal was converted to a digital signal through ADC. The digital signals were filtered using a band pass filter (BPF) with a range of 2.7 MHz to 4.4 MHz. The analysis range of the signal corresponded to about 50 to 90 mm from the sensor surface considering the transducer of focal length. The ensemble average value was calculated based on 50 pings received every 3 min.

To obtain marine environmental data, including water temperature and salinity, an environmental sensor (3919A CT sensor, Aanderaa, Bergen, Norway) was installed at the same depth as the acoustic sensor. Internal temperature and global positioning system (GPS) sensors were deployed for efficient system management and to determine location.

The network component received the acoustic and environmental data from the sensor. To reduce destabilization of transmission, dual internal and external antennas were installed. A notification function was employed using a lamp. The converted digital data were transmitted to the base station using a code division multiple access (CDMA) modem connected to a computer through the Internet. All data were displayed as a user application program (UAP) and web page. The UAP was used to store data, remote control and analysis of multiple systems. The power component used 220 V input voltage and efficiently supplied input power to each board.

Performance evaluation

C. polykrikoides was cultivated in f/2 medium in 100-L marine microcosms for 1 month (Guillard 1975). The culture medium was supplied with a light intensity of 80 μmol/m^2/s irradiance at 20°C on a 12:12 h light/dark cycle (Lee et al.

2001; Bok et al. 2010). To measure the acoustic signals, the cells were placed in a small flask and uniformly distributed using a stirrer. The acoustic signal was measured from cultured *C. polykrikoides* at abundance levels of 0 (no *C. polykrikoides*), 150, 300, 1,000, and 1,800 cells/mL in the laboratory. We compared the number of cells using an optical microscope (BX50, Olympus, Waltham, MA, USA) with the signals received.

In the ocean, backscattering signals were acquired in winter of 2013 using the system. Summer measurements were taken during 3 years (2013~2015). Fig. 2 shows an experimental site at a fish farm located in the marine research center, Korea Institute of Ocean Science & Technology (KIOST) off the southern coast of Korea. To minimize signals caused by bubbles, the sensor part was located at a depth of 1.5 m based on the e-folding depth (Crawford and Farmer 1987). Additionally, a hydro-wiper (Hydro-wiper, Zebra-Tech LTD, Nelson, New Zealand) was installed to clean the sensor surface once every 15 min to prevent noise caused by marine life. The acoustic detection system was operated for about 1 to 3 months during each summer. The measured data were transmitted in real-time through CDMA communication and confirmed on a computer. Water sampling was performed at the same depth as the sensor at specific times. The collected water was fixed with Lugol's iodine solution in a 500-mL bottle that blocked light (Guillard 1975). Phytoplankton populations were measured on an optical microscope using filtration after concentration in the laboratory.

3. Results

Performance evaluation in the laboratory conditions

Backscattering signals were measured totally eight times at five different cell densities under the same conditions using the developed system in the laboratory. To measure the representative mean received level at each measurement, 100 pings were used. The 0-cells/mL (no *C. polykrikoides*) observation used filtered seawater. Fig. 3 shows the RRL

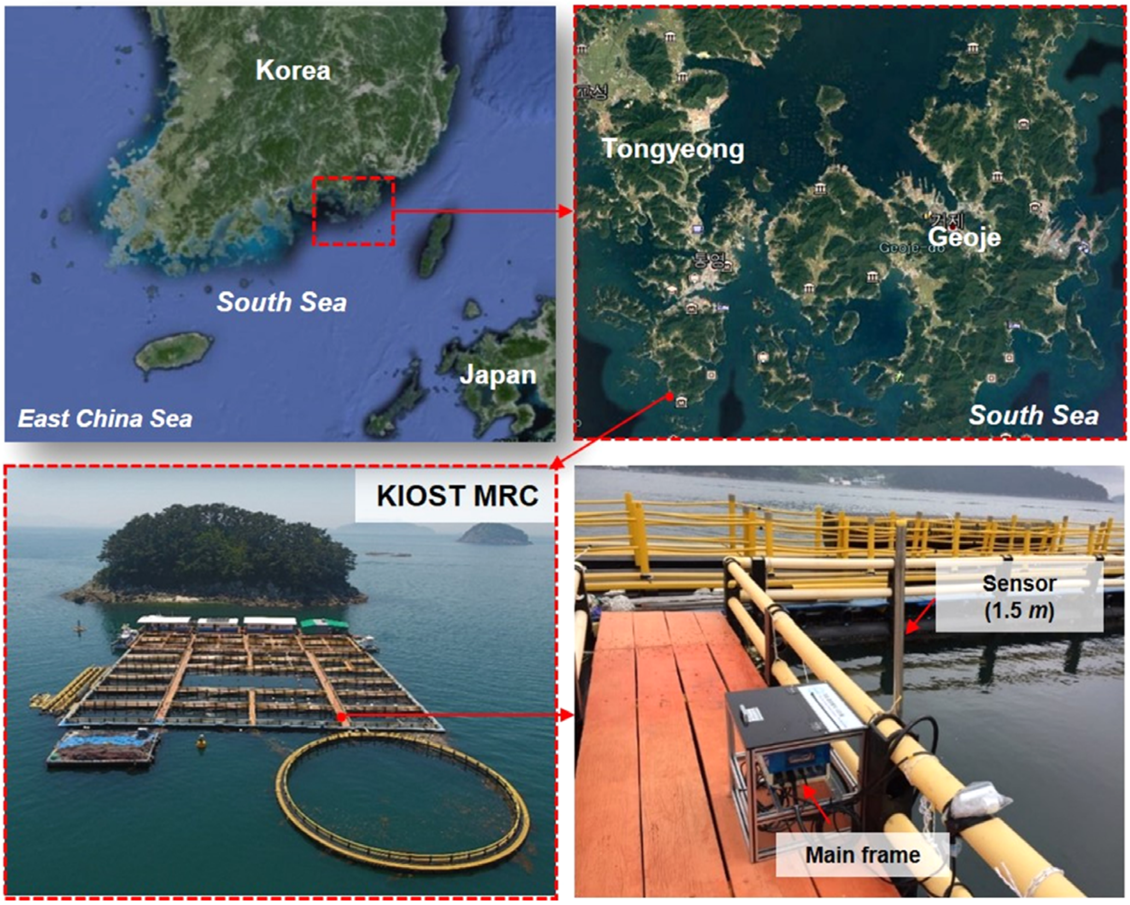

Fig. 2. Installation site of the real-time acoustic detection system for red tides in the southern coast of Korea

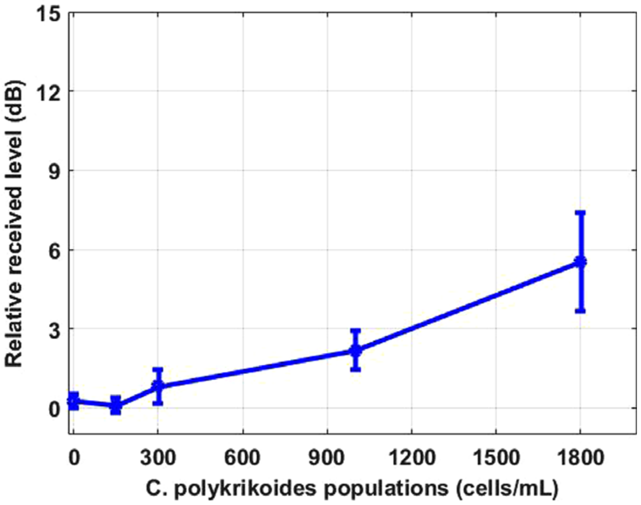

Fig. 3. Results of the system performance evaluation performed in the laboratory

versus the number of *C. polykrikoides*. The mean of the RRL ranged from 0 to 5.5 dB when *C. polykrikoides* populations were 0 to 1,800 cells/mL. There was significant change in RRL value with the number of cells in that, overall, the RRL showed a tendency to increase with increasing cell population. The possible reasons for the few minor differences for the 150 cell/mL condition were considered to be related to two factors; low cell activity, and the splitting of the cell chain. Totally, there was a significant correlation between backscattering signal levels and the number of cells from the several measurements.

Performance evaluation in field conditions

The measurements were performed in environments where red tides are sometimes observed in the ocean. Acoustic signals were acquired during winter every 6 s for 100 min in the environment of a waning red tide off the southern coast of Korea. Fig. 4a shows the results without red tide. The *in situ* signals received were close to 0 dB and had an almost constant mean value.

On the other hand, backscattering signals were also received when many red tides occurred in this region during the summers from 2013 to 2015. The acoustic data were averaged for 50 pings, which were acquired every 3 min. *C. polykrikoides* exhibited low acoustic levels as single cells, but formed a patch in seawater. The acoustic signals gradually increased, and high acoustic levels appeared for a long period of time due to the patch form.

We deployed the system *in situ* for about 3 months in 2013. During this time, there was a massive bloom that appeared to last longer than a month. Fig. 4b shows that the received acoustic signals increased first in the pre-caution stage and took a week to proliferate to the warning stage. After the bloom reached the warning stage, the acoustic signals showed diel vertical migrations (DVM) during the day and the night for 2 weeks. During this time, *C. polykrikoides* moved near the sea surface during the day to perform photosynthesis, but it was found near the bottom at night. This DVM pattern was apparent based on the signals received. The RRLs were about 25 dB during the day and less than 3 dB at night. The maximum *C. polykrikoides* population was 5,780 cells/mL. The RRL for this population was about 27 dB.

The warning stage occurred six times in 2014. The maximum RRL was 18 dB. The DVM pattern was similar to data from 2013, as shown in Fig. 4c. However, the acoustic signals cannot be compared with biological data because water sampling was not conducted regularly in 2013 and 2014.

Additionally, we compared the acoustic signals with biological data collected in 2015 (Fig. 4d). The warning stage occurred six times during that deployment. We performed continuous sampling at the same position and the same depth as the acoustic sensor. We found that the RRL was about 3 dB when *C. polykrikoides* was about 304 cells/mL; however, when the densities were 950 and 3,356 cells/mL, the RRLs were about 5 dB and 17 dB, respectively. Based on these results and previous work (NFRDI 2014), we determined levels for the designations of no red tide, the pre-caution stage, and the warning stage. To rule out the influence of other microorganisms, no red tide was deemed present at less than 2 dB, whereas the pre-caution stage was 2 dB to 5 dB, and the warning stage featured signals above 5 dB.

Real-time monitoring

We obtained acoustic, water temperature, salinity, GPS, intra-system humidity, and voltage data from the system developed in this study. The data were transmitted in real-time to the base station through CDMA communication. The transmitted data were visualized for monitoring. Fig. 5 shows the administrator program and web page for real-time monitoring that we developed to detect red tides. The administrator program can be checked in real-time for the received data, system performance data, and GPS position using Google Maps. The administrator controls the system connection, measurement time and exposition time using the remote-control feature. As the web page was publicly

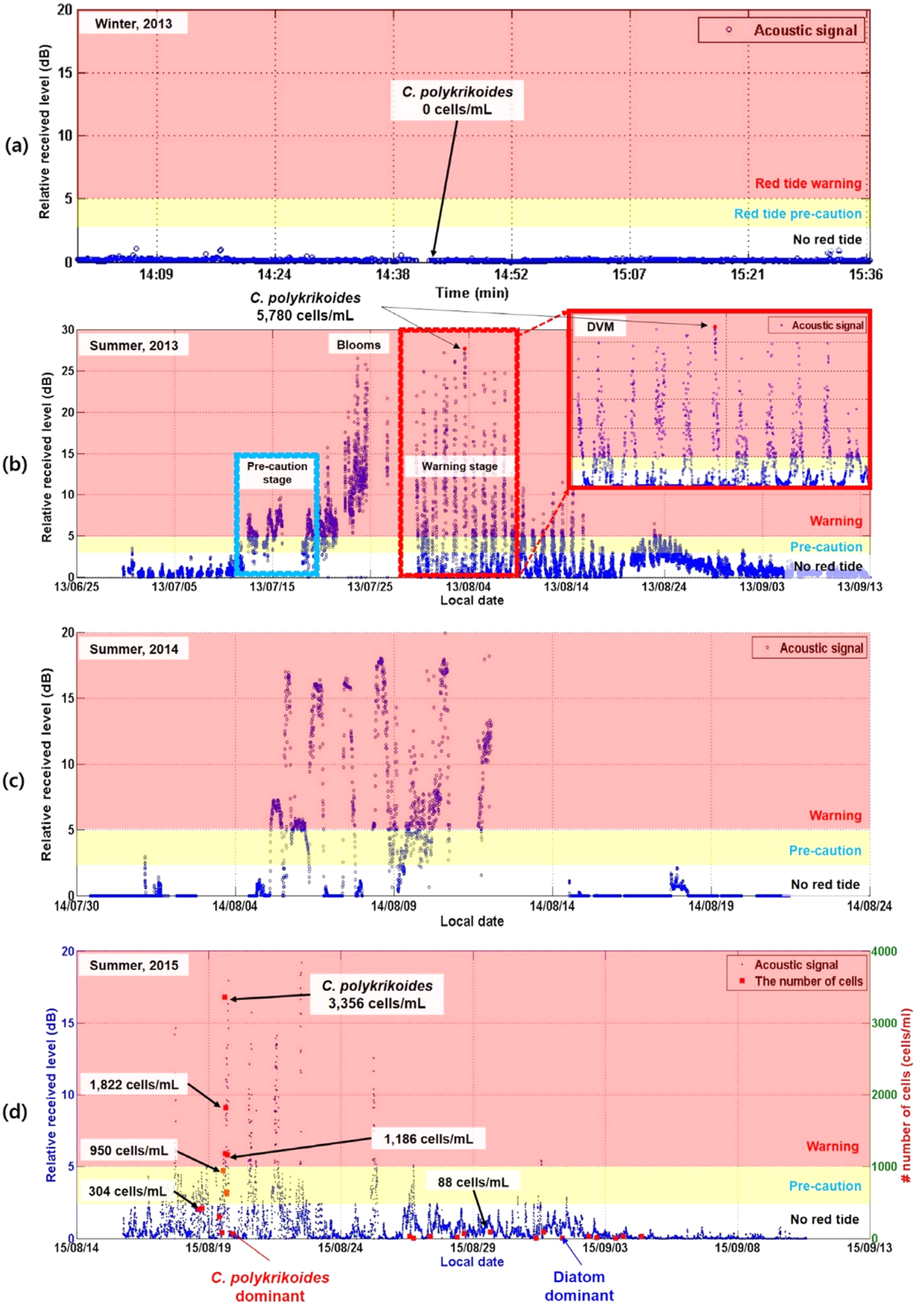

Fig. 4. Results of the acoustic signals under conditions of no red tide, pre-caution, and warning in the ocean during (a) winter 2013, (b) summer 2013, (c) summer 2014, and (d) summer 2015. Blue points represent acoustic data, and red points show biological data

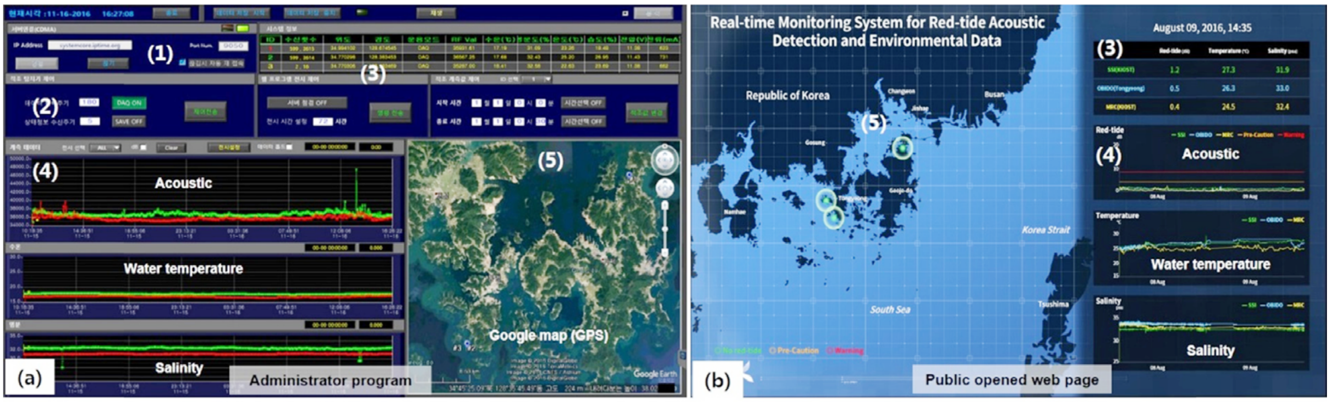

Fig. 5. Wireless data transport and remote-control components of the real-time acoustic detection system for red tides. (a) The administrator program graphic user interface (GUI), and (b) the public web page. (1) System set up; (2) server connection and on/off control; (3) environmental data; (4) acoustic, water temperature, and salinity data; and (5) GPS location on map

available, fishermen and public agencies were also able to check the real-time acoustic and environmental data. Moreover, when the data transmission was cut off or a red tide was detected, the administrators received a text message on their cell phones.

4. Discussion

The detection of red tides was carried out using a sea-cage type system with improvements in performance implemented based on our previous study (Kang et al. 2013), including buoy, ship-based, and portable models. The system developed in this study was evaluated and verified by operating the ultrasonic digital sensor in the laboratory and the ocean.

Research on phytoplankton has been primarily conducted by measuring photosynthesis or the number of cells in a water sample (Ahn et al. 2005). These methods are accurate but require excessive labor, money, and time for microscopic observation. Wide-area detection methods may be employed using satellite data. However, these methods do not detect blooms in the pre-caution stage when cell numbers are low. The accuracy and resolution of these images were low because the analysis area included land in the coastal area where fish farms were located (Ahn et al. 2005; Angles et al. 2008). Lee et al. (2005) developed a real-time observation system that used automatic water sampling and measurement of chlorophyll fluorescence, dissolved oxygen, and other hydro-meteorological variables in Hong Kong. The system was complicated, and the measurement interval was long. In this paper, we developed a simpler system using ultrasound and performed early detection of red tides.

The 3.5-MHz ultrasonic transducer was less likely to detect fish or zooplankton signals because of the narrow beam width and the short focal depth. However, when the signals showed abruptly high levels, the signals were judged to be noise. To remove these false targets, we applied the moving average method and threshold level (Loukas et al. 2015). Red tide species generally have limited or no swimming ability and form a biological patch over a certain size (Weiss and Provenzale 2008). On the other hand, nekton or fish have a strong swimming ability and don't form a patch (De Santo 1978). A total of 50 individual pings for calculating the average RRL was used and the elapsed time was within a much shorter period than 1 s. Therefore, although almost all transmitting signals had a low probability of hitting the nekton or fishes, coincidently some signals were influenced by unwanted targets with a swimming ability. To overcome this problem, as averaged RRL values for 1 or 2 data sets became suddenly higher than the threshold level, the unusual RRL values were fully removed during the post-processing stage. Otherwise, the moving average method was used with suitable RRL values below the threshold level. The threshold value was based on the previously measured reference data *in situ*.

The backscattering signals of *C. polykrikoides* cells differed between the laboratory and the ocean. Most *C. polykrikoides* appear as single or double cells of a chain in the laboratory, whereas cell chain composed of 4 to 16 cells are dominant in the ocean. The RRL was about 3 dB when the *C. polykrikoides* density was 1,000 cells/mL in the laboratory, but it was just under 5 dB when the density was 950 cells/mL in the ocean. The acoustic detection method could not classify the species present. Phytoplankton usually reveal the dominant growth of either red tide species (Dinoflagellates, *C. polykrikoides*) or non-red tide species (Diatoms). We did not make comparisons using all data but analyzed biological data from water sampled on several occasions in 2015. *C. polykrikoides* is dominant in the environment when the backscattering signal is high due to blooms. The backscattering range was short because we used a high-frequency signal. The system cannot detect broad areas, but the red tide phenomenon occurred primarily in patch form over a wide area.

5. Conclusions

In this study, we developed a real-time acoustic detection, remote-control, and monitoring system for the detection of red tides using an ultrasonic digital sensor. The advantages of the acoustic detection method are that measurements can be taken 24 hours a day and red tides can be detected early and in real-time. The stability and effectiveness of the system were verified through performance evaluation in the laboratory and in the ocean. In the laboratory, the backscattering signals increased as the number of cells increased. Detection of red tides in the pre-caution and warning stages was possible in the ocean. We installed the sensor *in situ* for 1 to 3 months in summer. We found a strong correlation between the acoustic signal and the *C. polykrikoides* population in 2015. This method appears promising for the early detection of red tide initiation. Additionally, the system can provide an alarm when a red tide is detected.

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