A continuous, real-time water quality monitoring system for the coral reef ecosystems of Nanwan Bay, Southern Taiwan

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1. Introduction

Nanwan Bay, which is within Kenting National Park (KNP), is located at the southernmost tip of Taiwan and supports one of the most highly biodiverse marine ecosystems in Taiwan, likely as a result of its highly dynamic water flow regime from its physical connection to the Luzon Strait (Lee et al., 1999a,b). The scenic landscape of Nanwan Bay has led to an explosion in ecotourism, which, unfortunately, threatens the ecological integrity of this unique environment. Specifically, in response to the rapid expansion of tourism, farmland destruction has increased along the Kenting coast to accommodate large construction projects, such as hotels. Furthermore, increasing tourist numbers threaten to place an excessive anthropogenic burden on the natural environment via increased coastal development, fisheries activities, sewage and other pollutant discharge, and consequent eutrophication (Meng et al., 2007a,b, 2008; Liu et al., 2012).

The KNP coral reef ecosystems are on an ongoing trajectory of degradation, as evidenced by regional patterns of coral and fish declines (Liu et al., 2009; Kuo et al., 2012). The coastal area of Nanwan Bay is also threatened by the thermal effluent water from a nearby nuclear power plant, which has directly led to coral bleaching (Huang and Hung, 1987; Hung et al., 1989; Su et al., 1987, 1989) and other negative impacts on the marine biological community (Chou et al., 2004). In addition, coral disease outbreaks (Liao et al., 2007), sea anemone outbreaks (Hung et al., 1998), overfishing and poaching (Polunin and Roberts, 1996), and snorkeling-induced coral destruction (Meng et al., 2007a,b) have also contributed to the deterioration of KNP’s coral reef ecosystems. Furthermore, physical disturbance and sedimentation by typhoons (Rogers, 1990; Hung et al., 2010; Kuo et al., 2011; Shih et al., 2013), cold water intrusion onto the shelf during spring tides (Lee et al., 1997, 1999a,b), and other natural phenomena have negatively affected the coral reefs within Nanwan Bay. The lack of seawater quality data both before and after such unpredictable marine incidents (Su et al., 1989; Hsieh et al., 2008) as well as, more generally, the absence of a long-term seawater quality dataset, thwarts efforts to determine how seawater quality changes affect the coral reef environments of Nanwan Bay. As such, there is a need for a long-term, real-time data collection system to monitor seawater quality within Nanwan Bay.

There is an increasing amount of evidence to suggest that changes in temperature and acidification associated with global climate change can adversely affect coral reefs (D’Croz and Maté, 2004; Cao et al., 2007; Hoegh-Guldberg, 1999; Hoegh-Guldberg...
et al., 2007; Veron, 2008). Electronic precision instruments for ocean monitoring and transmission technologies are constantly being improved such that the ability to collect seawater quality data in real-time over a long-term timescale is extremely feasible. These technologies can therefore facilitate our understanding of, for instance, how climate change will influence not only temperature and pCO₂, but also other seawater quality parameters, such as water quality, and how such cumulative seawater quality changes will affect the biology of these ecosystems. Furthermore, international advances made to protect marine environments rely on continuous, real-time systems to monitor abiotic factors of coral reef systems. Currently, the coral reef warning system is dominated by the U.S. National Oceanic and Atmospheric Administration (NOAA), which monitors 24 coral reef systems around the world using the Degree Heating Weeks (DHW) indicator (http://coral-reefwatch.noaa.gov/satellite/current/products_vs.html).

Presently, Nanwan Bay is not monitored with a coral reef warning system. In this study, we introduce a continuous real-time monitoring system that collected seawater quality data within Nanwan Bay. Furthermore, we demonstrate the utility of the data collected with this system by investigating biological and ecological processes affected by rapid temperature changes, including coral spawning. As such, this study provides a considerable contribution and an important first step to the conservation and scientific study of the coral reef environments of Nanwan Bay and KNPs.

2. Materials and methods

The continuous, real-time monitoring system (CRTMS) consists of a wireless transmission system and a solar panel that was mounted to a buoy anchored to the seafloor near the nuclear power plant (NPP) inlet (Fig. 1). The multi-parameter water quality sondes (YSI 6600) includes sensors to measure temperature, conductivity, sea level, pH, turbidity, and dissolved oxygen (DO). The specifications for precision and accuracy for all measured parameters are shown in Table 1 and were conducted following our governmental QA/QC regulations with the EPA/ROC (Taipei) methods. The procedure and frequency of periodic calibration of the equipment used in the monitoring must be specified. In this study, we calibrated the sensors every two weeks for all parameters; the frequency of all parameters measurement is ten minutes. The percentage of relative error for all the parameters reached the acceptable range after calibration.

Table 1: The specifications for precision and accuracy of all measured parameters.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Accuracy (%)</th>
<th>Precision (%)</th>
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<tbody>
<tr>
<td>Temperature</td>
<td>99.9</td>
<td>0.8</td>
</tr>
<tr>
<td>Salinity</td>
<td>99.9</td>
<td>0.18</td>
</tr>
<tr>
<td>pH</td>
<td>99.9</td>
<td>0.43</td>
</tr>
<tr>
<td>Dissolved oxygen</td>
<td>100.4</td>
<td>4.55</td>
</tr>
<tr>
<td>Turbidity</td>
<td>100.3</td>
<td>6.12</td>
</tr>
</tbody>
</table>

Salinity: IAPSO STANDARD SEAWATER (Batch: P152, 34.993 psu).
P: Merck Buffer pH4, pH 7, pH 10 and traceable to Standard Reference Material (SRM) from NIST and PTB.
Dissolved Oxygen: Air saturation.
Turbidity: HACH Formazin Turbidity Standard: 4000 NTU.

The CRTMS was deployed at a living coral reef in Nanwan Bay at 10 m depth (Fig. 2, N21°57.016', E120°45.372'). The measured data was transmitted to a control center at Taiwan's National Museum of Marine Biology and Aquarium (NMMBA) via wireless transmission of General Packet Radio Service (GPRS). In addition to instant access, the real-time data acquired was appended to historical information within a database at the control center. Lastly, if any abnormal condition occurred, an immediate warning signal was set to display at the control center so that personnel could act accordingly and back up all monitoring data. Additional analysis of phosphate, nitrate, nitrite, and ammonia concentrations was measured every 3-months as described in Liu et al. (2012) and appended to the database.

Corals of Southern Taiwan have been shown to be stressed when the sea surface temperature (SST) is 1 °C warmer than the maximum monthly mean (MMM; Tung et al., 2007). As such, one degree above the MMM is referred to as the “bleaching threshold” temperature. Degree Heating Weeks (DHW) is an indicator to determine the magnitude of coral bleaching in a short time period (http://coralreefwatch.noaa.gov/satellite/current/products_vs.html). A value of 1 in the DHW index (0–16) indicates that the seawater temperature
exceeded the coral bleaching threshold of 1 °C for at least one week or exceeded 2 °C for at least half of a week (Liu et al., 2003, 2006).

3. Result and discussion

Data collected from the CRTMS indicated that there was less than 5% relative error for all seawater quality parameters measured. As expected, there was a significant positive correlation between DO and pH (Fig. 3), due possibly to the effects of photosynthesis and respiration on pH and DO by organisms such as phytoplankton and algae. Temperature varied seasonally within Nanwan Bay with peak surface seawater temperatures exceeding 29 °C in the summer and dropping to ~22 °C in the winter. In addition, temperature and DO concentration mirrored tidal fluctuations in Nanwan Bay (Fig. 4). Specifically, temperature declined from 26.7 to 22.4 °C at a rate of 1.4 °C per hour as the tide raised, with declines in temperature by as much as 9 °C during the full moon and the new moon. This phenomenon was likely due to upwelling of cold water that intrudes into the shallow regions of Nanwan Bay during spring tides (Lee et al., 1997). Significant mortality events have been triggered by such sudden temperature changes in the past. For example, in November 1988, rapid declines in water temperature in Nanwan Bay induced extensive die-offs of coral reef fish (Su et al., 1989). In January 2008, a large number of coral reef
fish were found washed ashore on the northern beaches of the Penghu Archipelago (23°10′–50′N; 119°20′–50′E), which also coincided with a rapid drop in temperature, from 23.08 °C to 11.73 °C over the course of a month (Hsieh et al., 2008).

Previous studies have suggested that several environmental factors play important roles in determining the timing of mass coral spawning, including temperature, lunar periodicity, illumination, tidal surge, physical and chemical shock, presence or abundance of food resources, and others (Giese and Pearse, 1974; Harrison et al., 1984; Shlesinger and Loya, 1985; Kojis, 1986; Babcock et al., 1986, 1994; Richmond and Hunter, 1990). The historical records over the past two decades indicate that coral spawning within Nanwan Bay typically occurs between lunar March 20 and 24. The entire event typically lasts for 6 h during the night, with the majority of the spawning occurring during a 3 h peak period. Historical observations indicate that if there is little or no coral spawning activity by March 22, gametes that are not released by this time are usually released the following month (around April 20 to April 24) (personal communication with Mr. Yong Chun Tsai). Data collected from the CRTMS indicated little variation among seawater quality parameters with the exception of temperature, which showed large changes before and after coral spawning in March 2010–2011 (Fig. 5). The temperature was lower in 2011 compared to 2010 and this may have led to the delay in the predominant spawning event, which occurred in April, rather than March.

Regionally significant mass bleaching of corals was first observed in the late 1970s and was soon correlated with abnormally high sea temperatures, especially pulses naturally induced by El Niño events. El Niño events currently recur every 4–7 years (Glynn, 1984, 1990, 1991) and may be superimposed on generally elevated sea temperatures due to global warming (Hoegh-Guldberg, 1999). Mass bleaching events have been observed in Southern Taiwan in 1998 and 2007 (Dai et al., 1999; Tung et al., 2007). Currently, the Coral Reef Early Warning System (CREWS) carried out by NOAA does not monitor Nanwan Bay, despite the unique coral ecosystems found therein. In this study, we reviewed the related references of NOAA’s CREWS and calculated thresholds of coral bleaching based on the data collected from the CRTMS during 2010. Bleaching thresholds were found to depend on the ambient water temperature of the coral. As mentioned before, one degree above the MMM is referred to as the “bleaching threshold” temperature. According to calculations from Nanwan Bay (NPP inlet) the coral bleaching threshold is 29 °C (Fig. 6). The results showed that the DHWs ranged from 0.59 to 0.92 during the summer (approximately from June 20 to September 20, shown in Fig. 6) of 2010 (Fig. 7). The DHW scale ranges from 0.0 to 16.0 degree-weeks, when DHW values are greater than 1, sporadic coral bleaching is likely to occur. By the time DHW values reach 8, widespread bleaching is likely and some mortality can be expected (Goreau et al., 2000; Wellington et al., 2001; Strong et al., 2004; Coral Reef Watch, 2003; Liu et al., 2003, 2006; Eakin et al., 2010).

According to the CREWS, there are five defined stress levels (Table 2). In 2007, the SST data of Nanwan Bay indicated that the DHW was 1.03 in mid-July, during which sporadic cases of coral bleaching were observed (Tung et al., 2007). During August and

<table>
<thead>
<tr>
<th>Stress level</th>
<th>Definition</th>
<th>Effect</th>
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<tr>
<td>No stress</td>
<td>HotSpot ≤ 0</td>
<td>No bleaching</td>
</tr>
<tr>
<td>Bleaching watch</td>
<td>0 &lt; HotSpot &lt; 1</td>
<td>Possible bleaching</td>
</tr>
<tr>
<td>Bleaching warning</td>
<td>1 ≤ HotSpot, 0 &lt; DHW &lt; 4</td>
<td>Bleaching likely</td>
</tr>
<tr>
<td>Bleaching alert level 1</td>
<td>1 ≤ HotSpot, 4 ≤ DHW &lt; 8</td>
<td>Mortality likely</td>
</tr>
<tr>
<td>Bleaching alert level 2</td>
<td>1 ≤ HotSpot, 8 ≤ DHW</td>
<td></td>
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</table>

Fig. 5. Days before and after the coral spawning period in 2010 and 2011 in the coral reef ecosystems of Nanwan Bay, Southern Taiwan.

Fig. 6. Temperature logged between June and October in 2010 and 2011. The bleaching threshold temperature has been shown to be at 29 °C. Vertical lines indicate the summer period.

Fig. 7. Degree Heating Weeks (DHWs) ranging from 0.59 and 0.92 within the summer periods of 2010 and 2011, respectively, in the coral reef ecosystems of Nanwan Bay, Southern Taiwan.
September, the DHWs were above 5 and fell within the “Bleaching Alert Level 1” in CREWS category, and severe coral bleaching was indeed observed on certain KNP reefs at this time (Tung et al., 2007). In this study, the results showed that the temperature often exceeded the bleaching threshold by about 1 °C, and lasted about two weeks during the summers of 2010 and 2011. However, the DHW value at that time was less than 1, due to daily fluctuations in temperature generated by tidally driven cold water upwelling. As such, no bleaching occurred during this time.

Many studies have shown that cold water upwelling characterizes shallow regions of Nanwan Bay at certain times of the year, particularly the summer (Lee et al., 1997). Upwelling affects not only temperature, but also other abiotic seawater quality parameters (Fig. 8). This rapid decline in temperature in coastal regions could be a result of many processes, including internal tides (or waves), tidal current-induced eddies, long shore wind induced seaward Ekman transport, tropical cyclones, and movement of the boundary current front (e.g., Kuroshio) (Jan and Chen, 2009). The upwelling of cold water increases vertical mixing and regulates the temperature of Nanwan Bay in the summer. As a result, these processes will likely reduce the cumulative heat effects and therefore the likelihood of coral bleaching.

Climate change could potentially increase the intensity and frequency of both extreme hot and extreme cold events. The sensitivity of corals and their endosymbiotic Symbiodinium populations to rising ocean temperatures has been documented extensively. For example, when temperatures exceed summer maxima by 1–2 °C for 3 to 4 weeks, this obligatory endosymbiosis disintegrates with the ejection of the symbionts and results in coral bleaching (Hoegh-Guldberg, 1999). A recent study found that hot and cold water exposure causes distinct physiological responses at different time scales in the reef-building coral Acropora yongei, and these results suggest that short-term cold water exposure is more damaging for this branching coral than short-term warm water exposure (Roth et al., 2012). On the other hand, long-term elevated temperature exposure was found to be more harmful than long-term depressed temperature exposure (Roth et al., 2012). Hence, these studies suggest that the response of corals to elevated seawater temperature varies with species and environmental background history (Leichter et al., 2006; Barshis et al., 2010; Putnam and Edmunds, 2009; Putnam et al., 2010).

A magnitude 9.0 earthquake (“Tohoku”), which occurred on March 11, 2011, triggered warnings of tsunamis as high as 10 meters. The Pacific tsunami warning center indicated that the tsunami warning was in effect for Japan, Russia, the Marquesas, Northern Marianas, Guam, Taiwan, Philippines, Indonesia, and Hawaii. The Taiwan Central Weather Bureau issued a tsunami warning and the waves arrived at northern and Eastern coastal areas at around 5:36 p.m. and 5:44 p.m. Taiwan local time, respectively. As another example of the utility of the CRTMS, the earthquake caused a ca. 50 cm rise in the sea-level (Fig. 9). As such, the measuring of seawater quality both before and after a natural disaster could...
represent an important step in understanding how such disasters can directly, or indirectly, affect coral reef ecosystems.

4. Conclusions
Coral reefs are particularly vulnerable to environmental changes, and there is growing evidence for synergies among certain stressors, such as sea-level changes, storms, over-fishing, water quality deterioration, temperature increases, and ocean acidification (Emanuel, 2005; Church and White, 2006; Miller et al., 2006; Bruno et al., 2007; Harvell et al., 2007; Hoegh-Guldberg et al., 2007; Hughes et al., 2007; Anthony et al., 2008; Meng et al., 2008; Veron, 2008; Liu et al., 2012). This study described the implementation of a real-time seawater quality monitoring system for a select coral reef ecosystem by combining a multi-parameter seawater quality sonde with a wireless transmission system. The goal was to monitor the seawater quality to facilitate the understanding of how ambient seawater conditions near a coral ecosystem change in response to anthropogenic (e.g., sewage discharge, thermal effluent from a power plant) and natural disturbances (e.g., typhoons and upwelling). This monitoring program has been approved to serve as a member of the Coral Reef Environmental Monitoring System’s Near-Real Time Satellite Global Coral Bleaching Monitoring Program.

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References


