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Establishing an Ocean Acidification Monitoring System for the Tropical Waters of Indonesia Facing Regional Climate Variability

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ABSTRACT The emission of greenhouse gases, including high CO₂ and other materials, initiates global warming and climate change. Atmospheric CO₂ that affects the carbonate system of seawater causes ocean acidification (OA). OA affects marine organisms directly, as well as humans economically and ecologically. Considering the high impact of OA and following the United Nations' Sustainable Development Goals, systematic research and monitoring of OA is necessary in Indonesia, whose seas play an important role in this emerging phenomenon. This review discusses the urgency of OA monitoring systems and suggests carbonate system monitoring, as well as carbon biogeochemistry. OA significantly affects marine production and alters ecosystem services, and it is likely to have an impact on habitats shifting from calcified to non-calcified and reducing benthic complexity. Its effect on calcifying organisms can also be found, i.e., coral calcification and/or dissolution of CaCO₃ of calcifying organisms. Acidity (pH), as well as the carbonate system variables of seawater, fluctuate, especially with variations in space and time. Coastal ecosystems that are directly affected by terrestrial input will have carbonate system variables that fluctuate more. The annual rate of decreasing seawater pH, especially over an open and large spatial scale, may indicate OA. Therefore, a monitoring system must be implemented to obtain systematic and comprehensive information on OA. Here, we also introduce a biogeochemical monitoring initiative for OA in Lombok with the established protocols. Improvement of many aspects, including analysis instruments, analysis methods, sample treatment, and sampling frequency will provide new insight into further research and monitoring of OA.

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1. INTRODUCTION

The emission of greenhouse gases (GHG), particularly carbon dioxide (CO₂), is increasing rapidly since the industrial revolution (Gustafsson et al. 2015). Within the last decade, the major contributor of CO₂ emissions is the burning of fossil fuels and land use change (Friedrich et al. 2012), causing the condition of a high-CO₂ world. The increase of CO₂ has been altering the composition of atmospheric gases and the global carbon cycle that later induces global warming and climate change. Moreover, the high concentration of atmospheric CO₂ will increase the carbon absorption to the ocean, altering the carbonate system of seawater and causing ocean acidification (Zeebe and Wolf-Gladrow 2001; Canadell et al. 2007; Turley and Findlay 2016). The Intergovernmental Panel on Climate Change (IPCC) Workshop on Impacts of Ocean Acidification on Marine Biology and Ecosystems (Field et al. 2011) defines ocean acidification (OA) as “a reduction in the pH of the ocean over an extended period, typically decades or longer, which is caused primarily by uptake of carbon dioxide from the atmosphere, but can also be caused by other chemical additions or subtractions from the ocean” (IOC 2018).

It has been estimated that the ocean is a net sink for atmospheric CO₂, albeit having shifted from a source to a sink over the last 50–100 years. This phenomenon can be due to increased atmospheric pCO₂, an increased burial of organic carbon coupled with eutrophication and increased net ecosystem production, and an increased CO₂ buffer capacity (Gustafsson et al. 2015). In normal conditions, the changes of pH have been buffered by carbonate ions (CO₃²⁻). However, the rate at which CO₂ is currently being absorbed into the ocean is too rapid, and consequently is altering the pH.

The condition of the high-CO₂ world seems to be consecutively altering climate variability and carbon fluxes in the seas throughout the world, including the Indonesian seas. The high concentration of atmospheric CO₂ will increase the absorption of CO₂ emissions, i.e. 30% of total anthropogenic CO₂ (Canadell et al. 2007; Turley and Findlay 2016). This condition will potentially cause the seawater to become more acidic. OA alters the biogeochemical cycles of many elements and compounds, e.g., the lowering of calcium carbonate saturation states (Ω_{Ar}), which impacts shell-forming marine organisms, from plankton to benthic molluscs, corals, and echinoderms (Doney et al. 2009).

Indonesia, as a part of Coral Triangle of Southeast Asia, has the highest marine biodiversity, especially of reef-associated organisms. Coral reefs provide economic benefits and ecological services (Lam et al. 2019), but they have faced many stressors in recent years (Ellis et al. 2019; Harborne et al. 2017). The rise in ocean acidity is one of those triggers. OA is considered a significant impact, both directly and indirectly on marine animals, particularly a group of calcifying organisms such as molluscs, some marine plankton, and scleractinian coral (Rodolfo-Metalpa et al. 2011; Cohen et al. 2009).

The Indonesian seas will potentially become more severely impacted by both climate change and OA. The geolocation of the Indonesian seas within the maritime continent is very likely affected by climate variability, and vice versa (Sprintall and Révelard 2014; Yamanaka et al. 2018; Sprintall et al. 2019). Increases in extreme weather, an indication that climate change is in progress, will ultimately have socioeconomic impacts. OA will also significantly affect marine production and alter ecosystem services. The cumulative effects of climate change and OA will likely increase the magnitude of the impact, both ecologically and socioeconomically.

Considering the high impact of OA and following the global responsibility set out in the Sustainable Development Goals (i.e., SDG 14), it is necessary to conduct systematic research and monitoring of OA in Indonesia. Here, we will inform on the background and the urgency of OA monitoring systems. We also suggest the carbonate system monitoring for OA, as well as carbon biogeochemistry studies.

2. REGIONAL VARIABILITY OF CLIMATE AND AIR-SEA CO₂ EXCHANGE IN THE INDONESIAN MARITIME CONTINENT

The Indonesian Maritime Continent has been known to have unique features in climate and atmosphere variability due to its geolocation as well as the Indonesian seas' features (Yu et al. 2016; Yamanaka et al. 2018; Sprintall et al. 2019). The Indonesian seas are situated at the climatological center of the atmospheric deep convection (Sprintall et al. 2019). Climate-driven phenomena such as Indian Ocean Dipole and El Niño–Southern Oscillation collocated within the Indonesian seas affect sea surface temperature (SST) anomalies on the western- and eastern-node, respectively (Annamalai et al. 2010; Koch-Larrouy et al. 2010).

The Indonesian Maritime Continent is also seen to have monsoon climatological features as the world's largest “regional” rainfall (Chang et al. 2005; Robertson et al. 2011; Yamanaka et al. 2018). This feature very likely affects the SST and salinity of the Indonesian seas. Furthermore, indications of increasing extreme La Niña shows the response to more extreme El Niños, an accelerated maritime continent warming and the increasing of SST (Cai et al. 2015).

The changes of SST may contribute to changes in partial pressure of CO₂ ($p\text{CO}_2$), which later will alter the air-sea CO₂ fluxes, or vice versa (Lefèvre and Taylor 2002; Jiang et al. 2008). In general, increases in SST will increase the CO₂ fluxes to the water column (Park et al. 2010; Mucci et al. 2010; Woolf et al. 2016). This condition will increase the concentration of the aqueous CO₂ or CO₂(aq)—i.e., the dissolved CO₂ in the seawater—in the surface layer of seawater up to the diurnal thermocline layer (Woolf et al. 2016). High concentrations of the aqueous CO₂ will be followed up by an iso-chemical response including the changes in the carbonate system equilibrium.

Regional variability of $p\text{CO}_2$ in the maritime continent would be represented by several waters including the South China Sea, Indonesian territorial waters, South-Western Pacific Ocean, and Equatorial Eastern Indian Ocean. Within these areas, the near-shore $p\text{CO}_2$ likely shows a very dynamic pattern associated with the regional hydrodynamic settings (Zhai et al. 2005). The air-sea CO₂ fluxes were a primary process that modulated surface $p\text{CO}_2$ and exceeded the role of the SST. However, it is clear that SST and air-sea CO₂ exchange is correlated with $p\text{CO}_2$. Another pattern shows that the phase of the $p\text{CO}_2$ variation generally follows the strong seasonal cycle of SST (Lu et al. 2012).

Based on the above facts, the climatic and ocean features of the maritime continent affect the dynamics of atmospheric and ocean carbon biogeochemistry. Moreover, the dynamics of the air-sea CO₂ exchange will certainly affect carbonate system variability (Cantoni et al. 2012).

3. CARBONATE SYSTEM VARIABILITY AS INDICATORS FOR OCEAN ACIDIFICATION MONITORING

Carbonate system variability has been widely known as an indicator of OA (Cantoni et al. 2012). The parameters of the carbonate system include pH, CO₂ partial pressure ($p\text{CO}_2$), dissolved inorganic carbon (DIC), carbonate ion concentration (CO₃^{2−}), aragonite saturation state (Ω_{Ar}), and total alkalinity (TA). Takahashi et al. (2014) reported that the main factor of OA is the uptake of atmospheric CO₂ and is driven with four environmental factors, namely temperature, salinity, alkalinity, and total CO₂ concentration.

When the oceans take up atmospheric CO₂, the dissolved CO₂ may react with seawater to form carbonic acid (H₂CO₃), a weak acid that rapidly dissociates to produce bicarbonate ion. This ion may further dissociate to produce carbonate ion. During the processes, hydrogen ion (H⁺), which is also known as a proton, is also produced. More CO₂ absorbed by the ocean means more carbonic acid and/or protons will be produced, resulting in the increase in seawater acidity (measured by lowered pH value). The pH is a numerical way of defining the hydrogen ion concentration of a liquid. It is the negative logarithm of the proton concentration, $-\log_{10}[\text{H}^+]$. Accordingly, pH is the primary indicator for ocean acidification, since the declining trend of ocean pH follows increasing atmospheric CO₂. For instance, long term observation of seawater pH to assess OA was conducted by Bates et al. (2012) for three decades (1983–2011) in North Atlantic subtropical gyre near Bermuda, and found a drop in seawater pH by 0.05 with a rate of -0.0017 yr^{-1} .

Since OA is a result of the accumulation of atmospheric CO₂ taken up by the ocean, partial pressure of CO₂ ($p\text{CO}_2$) in seawater will increase when ocean acidification occurs. In some regions, the increasing rate of surface ocean $p\text{CO}_2$ is similar to that in the atmosphere. Therefore, quantification of the amount of (CO₂) in seawater through $p\text{CO}_2$ measurement is an essential component of OA research. As an example, a decade-long (2004–2015) observation of $p\text{CO}_2$ to assess OA was made by Omar et al. (2019) in the northern North Sea. Their results showed a close inverse relationship between $p\text{CO}_2$ and pH where spatial and seasonal patterns of $p\text{CO}_2$ are opposites of the pH value. There was an increasing trend of $p\text{CO}_2$ with an annual rate of $2.39 \pm 0.58 \text{ } \mu\text{atm/year}$. On the other hand, the pH value was decreasing with an annual rate of $-0.0024 \pm 0.001 \text{ yr}^{-1}$. This condition indicates that OA is occurring within the region.

When OA occurs, a vast amount of atmospheric CO₂ is absorbed by the oceans. In seawater, this inorganic car-

bon will accumulate and exist in three species, free carbon dioxide ($\text{CO}_{2(\text{aq})}$), bicarbonate ion (HCO_3^-), and carbonate ion (CO_3^{2-}). The sum of those three species is known as dissolved inorganic carbon (DIC). The distribution between these three species depends on seawater pH. Since then, the uptake rate of anthropogenic carbon and OA can be tracked using DIC. The OA is usually accompanied by an increased level of DIC and decrease in carbonate ion level. The OA phenomenon associated with increasing DIC was reported by Huang et al. (2018). According to the report, DIC-solution injection may contribute to both decreasing ocean acidity and increasing seawater $p\text{CO}_2$. Nearly two decades of measurements (1988–2007) of surface seawater pH at station ALOHA in the central North Pacific Ocean also exhibited a decreasing annual rate of $-0.0019 \pm 0.0002 \text{ y}^{-1}$ in seawater pH, as predicted when ocean surface CO_2 is in equilibrium with that in the atmosphere (Dore et al. 2009). This indicates a strong correlation between ocean acidification and increasing DIC.

Although the DIC concentration is rising following the ocean acidification process, the carbonate ion as one of the DIC species is decreasing. Once dissolved carbon dioxide reacts with seawater to form hydrogen ion, the carbonate ion will bind up the hydrogen ion to form bicarbonate ion. As a consequence, when OA occurs, carbonate ion decreases while bicarbonate increases. When the carbonate ion concentration depletes, the aragonite saturation state (Ω_{Ar}) will also decline. Aragonite is one of the more soluble forms of calcium carbonate and is essential for marine calcifiers to build their hard structures. If the Ω_{Ar} value falls below 1, seawater is said to be undersaturated with respect to aragonite. In other words, mineral aragonite tends to dissolve. In contrast, a Ω_{Ar} value higher than 1 indicates that seawater is supersaturated with respect to aragonite, which means aragonite tends to precipitate. The aragonite saturation state is calculated by multiplying calcium (Ca^{2+}) ion and carbonate ion concentrations and then dividing the result with the solubility of aragonite in seawater at equilibrium. Since the aragonite saturation state represents a measure of carbonate ion, it is commonly used to track OA (Dore et al. 2009; Yamamoto-Kawai et al. 2009).

4. THE IMPORTANCE OF OA MONITORING

The impact of OA will significantly affect marine production and alter ecosystem services. Changes in the carbonate system will alter the survival rate of marine biota, the metabolism, and larval growth of fishes (Branch et al. 2013; Lannig et al. 2010; Bromhead et al. 2015; Turley and Findlay 2016). OA likely has impacted habitats shifting from calcified to non-calcified and reductions in benthic complexity (Cattano et al. 2020). Habitat changes that may be caused by the decrease of pH due to the change in the carbonate system will induce the decrease of fishery production in coral reef ecosystems. Conversely, it has also the potential to increase fishery production in seagrass meadows or algal beds (Branch et al. 2013; Koch et al. 2013). Seagrass meadows, as part of the coastal ecosystem, provide valuable nursery habitats to over 1/5th of the world's largest fisheries (Unsworth et al. 2019).

Corals are particularly under threat from OA conditions due to the requirement of a stable pH to allow their calcium carbonate skeletons to be accreted (Vargas-Ángel et al. 2015). Meanwhile, coral reefs that play multiple important roles throughout the tropic levels, housing biological diversity as well as providing key ecosystem goods and services such as a habitat for fisheries, are very likely to be-

come the most vulnerable ecosystems due to OA (Gattuso et al. 2015). Many studies have shown the effect of OA on coral calcification and/or dissolution of CaCO_3 . However, hermatypic corals can exhibit different calcification mechanisms between species and may have different responses to OA. The cauliflower coral, *Pocillopora damicornis*, displays an insensitive trait to lower pH while the staghorn coral, *Acropora youngi*, has been shown to have a reduced calcification rate under low pH conditions (DeCarlo et al. 2018). Corals are highly sensitive to environmental conditions, especially in their early life stage (Humanes et al. 2016). Investigations into the effect of lower pH on coral larvae found that the larvae of *P. damicornis* had a declining settlement rate when exposed to low pH treatments. Moreover, at pH 7.9 and 7.6 all coral larvae were not found to be able to complete metamorphosis (Viyakarn et al. 2015). These are associated with the decline of coral recruitment and coral populations, causing a significant reduction in coral cover (Richmond et al. 2018).

Significant impacts are also expected on several commercial marine species (Branch et al. 2013). An oyster farm in the west coast of the United States was found to have the lowest production in 2006, because of pathogens and unsuitable environment factors, especially in a Whiskey Creek hatchery where it was found that the seawater chemistry was changing when upwelling brought up the acidified water onto the surface containing high CO_2 consequences of the aragonite saturation and CO_2 concentration in the oyster farm (Barton et al. 2012). Under normal environmental conditions, green mussels create a biomaterial called a "byssal thread" to attach to the substrate. However, when evaluating $p\text{CO}_2$, the proteinaceous byssal thread was shown to be less extensible with weaker attachment strength to the substratum. The weakened attachment could reduce the potential of green mussel survival in the farm, resulting in lower quantities of harvest (O'Donnell et al. 2013). Low pH conditions negatively affect the physiological process of shelled molluscs, in both their juvenile and adult stages, such as shell growth (calcification), somatic growth, excretion, etc., when pH is dropped to 0.4 (Gazeau et al. 2013). Several studies have shown the numerous effects of OA on marine fish, such as neurosensory impairment, respiratory acid-base disturbance, and impacts on motility (Esbaugh 2018). Conversely, studies on the effect of OA on Baltic cod (*Gadus morhua*) showed impartial results at the 7.55 pH on sperm speed and motility, suggesting that OA may not play an important role in the sperm behavior of Baltic cod (Frommel et al. 2010). The potential for calcifying marine organisms' adaptation to ocean acidification is poorly understood while other marine animals may remain unscathed.

Ocean governance facing the potential impact of OA on marine production as protein sources is considered crucial. It has been known that Indonesia's consumption of fishes and fish products is 12.8 kg per capita per year (16.4% of total protein consumption). This demand is supported by marine-based products by up to 70% (Needham and Funge-Smith 2015). That means that OA will impact socioeconomic conditions nationally and regionally within the maritime continent.

Following up the United Nation's Decade of Ocean Science for Sustainable Development (DOSSD) that has been established for 2021–2030, the OA nationwide monitoring network would be beneficial for national and regional stakeholders. The DOSSD would be a common framework to support efforts on reversing the cycle of decline in ocean

health. Ocean research and observation will focus on the impact of multiple stressors on the marine ecosystems, including OA (Tilbrook et al. 2019). Therefore, establishing and applying OA monitoring systems will be the potential contribution to the regional or global agenda in ocean science. In order to measure the potential impact of OA, we have to assess the carbon dynamics within the ocean carbon cycle. Since the change of the ocean carbon cycle has been known to vary spatially and temporally, the systematic observation and studies of the carbon budget will be necessary, especially on carbonate system variability.

OA monitoring should be conducted within the scope of pelagic ecosystem and/or coastal ecosystems. Since the most important effects of elevated $p\text{CO}_2$ during the occurrence of OA are reduced calcification and changes in metabolism (Kelly and Hofmann 2013), OA monitoring in coastal ecosystems (i.e., coral reef and seagrass ecosystems) is relevant and important for archipelagic countries such as Indonesia. Furthermore, the importance of OA monitoring within the scope of coastal and continental shelf waters is due to fisheries' and maricultures' significant dependence on calcifying species (Gledhill et al. 2015).

5. THE PROPOSED BIOGEOCHEMICAL MONITORING SYSTEM FOR OCEAN ACIDIFICATION

Measurement of physical, chemical, and biological parameters need standard protocols to obtain valid data. Nowadays, the international standard for biogeochemical parameters is the result of the Intergovernmental Oceanographic Commission (IOC), as part of its custodianship role in relation to SDG 14 indicators (IOC 2018). Following up the regional program initiated by the IOC Western Pacific, the Research Centre for Oceanography initiated a pilot site in Sire, Lombok Island, Indonesia. The research and monitoring of OA started in 2018 up to the present.

5.1 Overview of physical and biological monitoring parameters

Several technologies have been developed for use in situ experiments to monitor ocean fluctuations, including mooring and micro-electrical-mechanical and even autonomous vehicles, etc. (Cole et al. 2019). Autonomous reef monitoring structures (ARMS) are artificial structures that are developed to examine and monitor the most diverse community of invertebrate organisms in coral reef ecosystems. These long-term collecting devices have been used to study coral reefs worldwide. ARMS were designed as a three-dimensional structure to mimic the structural complexity of hard bottom marine habitats (David et al. 2019). They are made from a PVC plate (size 9" × 9" × 9") and assembled with each plate as a layer forming to complete the ARMS unit (Ransome et al. 2017). To deploy the ARMS, the following three units are installed to the hard bottom at depths of 10–15 m and each individual unit is placed approximately 2–5 m apart. ARMS units are submerged underwater for at least 2 years. After the monitoring period, each unit is recovered and disassembled for data collection. Photographs are subsequently taken of each plate for sessile organism recruitment and composition analysis. After scraping the encrusting sessile and associated microbes on the plate, the samples are preserved in 95% ethanol for later taxonomic and metabarcoding analyses (Pearman et al. 2019). ARMS units are an inexpensive and standardized material to study biodiversity changes and may imply the link between the effect of OA and invertebrate diver-

sity that may have implications for conservation management (Ransome et al. 2017). In addition, monitoring of cryptobiota in coral reefs using ARMS is possible when studied together with geochemistry to understand the possible impact of environmental variables on marine creatures (FOARAM Act; Alsop et al. 2014).

Several studies on the calcification and dissolution of calcifying marine organisms and/or ecosystems to natural variability in pH have been published (Andersson and Gledhill 2013). Calcium carbonate accretion units (CAUs) are a tool to monitor calcium carbonate accretion rate changes in ocean habitats, such as coral reefs. Each CAU is an artificial structure consisting of a pair of non-toxic PVC plates of 10 × 10 cm, with each plate mounted with a stainless steel rod and separated by a spacer. CAUs are typically deployed at depths of 5–15 meters for one year or consecutively for 2–3 years. To deploy CAUs, an installation of an assembled unit is affixed to the reef substrate using underwater epoxy. After the completion of the experiment, CAUs are recovered and rinsed with salt water to remove mobile organisms, disassembled, and all organisms on the upper and lower surface of the plates are photographed and counted to quantify the benthic community and for taxonomic classification. To quantify the net CaCO_3 production accreted on CAUs, units are dried at 60°C for 2–5 days and then weighed. They are then submerged in 5% HCl until all CaCO_3 has dissolved. The remaining non-calcareous tissue is removed on pre-weight 11 or 15 μm cellulose paper, dried at 60°C until the material is stable, and weighed. Then, the acidified, scraped, and dried plate is weighed again to determine the difference in calcified to fleshy biomass. Total calcareous mass on CAU is divided by the total surface area of each CAU and the carbonate production present is calculated as $\text{g CaCO}_3 \text{ cm}^{-2} \text{ yr}^{-1}$ (Price et al. 2012; Vargas-Ángel et al. 2015; dos Reis et al. 2016). The result of calcium carbonate accretion on CAUs (net weight) allows for the investigation of changes in calcification rates over time. The accretion rate of CaCO_3 varies in different locations so CaCO_3 composition that is accreted on CAUs can be used to predict the percentage of surrounding benthos recruitment community following the variety of accreted materials. For example, the net accretion rate of CaCO_3 around reef areas is positively correlated with crustose coralline algae, indicating that crustose coralline algae may play an important role as a carbonate reef builder in reef ecosystems (Vargas-Ángel et al. 2015). However, shifting carbonate production in the ocean ecosystem may be visible in the near future due to OA impacts, leading to a loss of habitat complexity and biodiversity (Andersson and Gledhill 2013; Sunday et al. 2017; Mollica et al. 2018). Furthermore, effective research and monitoring are essential for ensuring the persistence of marine organism populations and for economic and ecological sustainability.

Accompanying the biological parameters, several physical parameters should be used for OA monitoring. Those parameters include sea surface temperature (SST), salinity, and water clarity. Temperature and salinity will be important parameters since they are closely correlated to the carbonate system (IOC 2018). Additionally, monitoring of temperature and salinity is relatively easy using sensor measurements (Lorenzoni and Benway 2013).

5.2 Biogeochemical monitoring parameters

The biogeochemical parameters for OA monitoring include pH on total scale and/or partial pressure of $\text{CO}_2/p\text{CO}_2$ (μatm or ppt), dissolved inorganic carbon/DIC ($\mu\text{mol kg}^{-1}$),

and total alkalinity/TA ($\mu\text{mol kg}^{-1}$). The pH fluctuation following the changes of carbonate system parameters is correlated with the biogeochemical process, i.e., changes of TA, DIC, and $p\text{CO}_2$ following the CO_2 transfer from and to the seawater. Individual data points for pH (hydrogen ion concentrations on a logarithmic scale) that are measured either directly or calculated based on data of two other parameters—TA, DIC, and $p\text{CO}_2$ —will be provided from the observation on the pilot site.

In order to determine the number, times, and places for sampling, the natural variability in ocean chemistry (in particular, seasonal variability) and the driving forces behind it (e.g., tides, seasons, runoff, rainfall, etc.) need to be considered in designing a sampling strategy (Karl 2010; Hofmann et al. 2010; Alin et al. 2015). Data points for pH and other parameters of the carbonate system can be highly variable in space and time. Therefore, it is important to consider the spatio-temporal resolution (Hofmann et al. 2011). The frequency of observation will depend on the parameter to be measured (e.g., average pH or minimum pH), the required accuracy, and the characteristic of the temporal variability at the sampling site. The coastal zone is often characterized by higher temporal variability in the carbonate chemistry compared with the open ocean, thus more data points are required to accurately capture the average pH. The number of observations needed to capture extreme pH values will also depend on their frequency and intensity (Hofmann et al. 2011). The guidelines for coastal OA observations have been published, i.e., by Dickson et al. (2007), Riebesell et al. (2011), and Pimenta and Grear (2018).

The common best practice for monitoring the carbonate system within the OA monitoring scope is detailed in the Requirements and Governance Plan of the Global Ocean Acidification Observing Network (GOA-ON; Newton et al. 2015). The practice includes the following approaches (IOC 2018):

1. "Collection of seawater samples for laboratory analyses of DIC and TA is a standard practice if ship or fixed platform access to the water allows. Parameters of interest, such as pH and aragonite saturation, can be derived via commonly available software (e.g., CO2SYS). Some calculations require nutrients and other variables."
2. "Sensors are only commercially available for measurements of pH and $p\text{CO}_2$ in the ocean. Currently, sensors capable of measuring either of these parameters with the high precision required to detect the ocean acidification signal are costly and require high maintenance."
3. "Use of empirical proxies, such as more easily and accurately measured variables (salinity, temperature, oxygen), to estimate pH and aragonite saturation has been tested for use in oceanic waters, but has yet to be established for estuarine waters where other factors may interfere."

McLaughlin et al. (2015) illustrated the uncertainty in calculating ocean carbon cycle parameters based on different measurements (Table 1). The list of standard operating procedures to measure different parameters of the carbonate system is resumed in Table 2.

We recommend that at least two out of four measurable parameters in the ocean carbon system (pH, $p\text{CO}_2$, TA, and DIC) are needed to "constrain" the carbonate system. Computer programs are commonly used to calculate other carbonate chemistry parameters from the measured parameters and many of these software packages are accessible by the public. In addition to the two carbonate system parameters, the software packages require temperature (in situ

at time of sampling and temperature at time of measurement, if different), salinity, and pressure (depth). Nutrient concentrations may be added to provide additional information. The calculations of the carbonate system should follow the recommendations made by Orr et al. (2015).

5.3 Indonesia's first pilot site for OA monitoring

Conducting ocean acidification monitoring in Indonesia is quite challenging due to its large oceanic area with different water mass characteristics in different locations. As such, data obtained from observations in just a few locations could not represent the whole of the country. Understanding the OA process in Indonesian water requires many observations from many locations. In addition, OA monitoring is a long term activity with minimum short-term usable results, making it a very costly study to conduct. On the other hand, there are very limited appropriate instrumentations to support the study. Human resources with sufficient capability in measuring the carbonate system is limited to cover all representative sites for an OA study.

Since OA is a global phenomenon, global awareness and collective action are required to deal with this issue. Indonesia realizes the importance of an ocean carbon observatory network to address the problem of OA adequately. Therefore, in the spirit of contributing to the implementation of SDG 14, the Research Center for Oceanography-Indonesian Institute of Sciences (LIPI), on behalf of Indonesia, has often been involved in the IOC-WESTPAC workshop on ocean acidification and recently established the pilot site for OA monitoring. Considering the aforementioned obstacles in conducting this monitoring, only one pilot site is established for the initial effort. With this strategy, it is expected that less cost is required for field sampling and measurement and continuity of monitoring is maintained.

The Indonesian pilot site for OA monitoring is in Sire Bay, Lombok Utara Regency, Nusa Tenggara Barat Province (Figure 1). It is located close to the Lombok Strait (8.361–8.368 S 116.112–116.117 E). It is selected among other candidates that include Bintan Island, Natuna Islands, and Pari Island. Some of the reasons for the decision are as follows:

1. The existence of coral reef and seagrass ecosystems. Coral reef and seagrass ecosystems exist in Sire Bay. Coastal marine ecosystems provide ca. 40% of the global ecosystem goods and services (Costanza et al. 1997). Many marine organisms rely on the availability of coastal habitats, including coral reefs and seagrass meadows. These habitats provide shelter as well as important feeding grounds for a range of organisms. It is important to understand how marine lives in these ecosystems respond to OA. In addition, it is also critical to study the role of seagrass meadows as a buffering system against OA due to seagrass's ability in CO_2 sequestration. Therefore, Sire Bay is a convenient site to study OA and its ecological impacts on coastal ecosystems.

TABLE 1. Combined uncertainties in calculated ocean carbon cycle parameters based on different measurements (McLaughlin et al. 2015).

Pairing	pH (%)	DIC (%)	TA (%)	$p\text{CO}_2$ (%)
pH & DIC	0.3	0.5	1	6
pH & $p\text{CO}_2$	0.3	7	7	3
DIC & TA	0.3	0.5	0.5	12
DIC & $p\text{CO}_2$	0.3	0.5	1	3

TABLE 2. List of standard operating procedures to measure different parameters of the carbonate system.

Parameter	Discrete	Underway	Fixed autonomous sensors ³
pH	Spectrophotometric*	Spectrophotometric	Spectrophotometric
	Potentiometric ¹	ISFET ³	ISFET ³
DIC	IR detection	-	-
	Coulometry* ¹	-	-
TA	Potentiometric titration ¹ (open and closed cell; open recommended)*	-	-
pCO ₂	-	Equilibration, headspace	Equilibration
	-	*Membrane-based ⁴	*Membrane-based ⁵
Temperature	Sensor measurements ²	Sensor measurements ²	Sensor measurements ²
Salinity	Sensor measurements ²	Sensor measurements ²	Sensor measurements ²

¹Dickson et al. (2007), ²Lorenzoni and Benway (2013), ³Bresnahan et al. (2014), ⁴Pierrot et al. (2009), ⁵Sutton et al. (2014); detail linked standard operation procedures may refer to the Intergovernmental Oceanographic Commission (2018) within the 14.3.1 SDG methodology.

- Minimum anthropogenic influence. Acidification of coastal ecosystems may occur through organic matter degradation, atmospheric CO₂ fluxes, riverine input of acidic water, and upwelling of CO₂ enriched deep water (Wallace et al. 2014). Since Sire Bay is in pristine condition with minimum anthropogenic inputs, external processes causing acidification in this site will be principally driven by atmospheric loading of CO₂. Accordingly, assessment of the response of corals and other marine calcifying organisms to increasing atmospheric CO₂-driven OA is reliable despite the ignorance of environmental pollutant stressors.
- Proximity to the Indian Ocean. The Lombok Strait is an interesting site to monitor OA due to its role as the exit passage transporting Pacific water toward the Indian Ocean. Water either from the Pacific or the Indian Oceans flows through this strait during different monsoon seasons, causing variability in temperature, salinity, and other properties Sprintall et al. (2019). The existing OA observatory stations are largely located and focused in the North Pacific and North Atlantic Oceans (González-Dávila et al. 2010; Ríos et al. 2015). Since there are fewer stations located in the Indian Ocean, the establishment of a pilot site for OA monitoring near the Lombok Strait and the Indian Ocean may contribute to providing new information on the changing condition of surface seawater pH in the eastern Indian Ocean.
- Technical support. The Research Center for Oceanography, Indonesian Institute of Sciences (RCO-LIPI), based in Jakarta, has a research station in Lombok. Accordingly, a big team of researchers from RCO-LIPI is not necessary to come frequently to Lombok for collecting discrete samples and time series data for an OA study. Samples and time series data can be collected by only a small team from RCO-LIPI with some help from researchers based in Lombok instead. The provision of field work support from researchers at the research station makes for efficient high frequency sampling.

Carbonate system parameters including pH, total alkalinity (A_T), partial pressure of CO₂ (pCO₂), and dissolved inorganic carbon (DIC) are common parameters measured in OA studies. Although measuring two of those parameters is sufficient to calculate the other two, we directly measure three out of four parameters, excluding DIC, to assess ocean acidification in the monitoring site. We also measure water quality parameters such as temperature, salinity, dissolved oxygen (DO), nutrients, and chlorophyll-*a*. These parameters usually have a close relationship with carbonate system parameter variability.

Seawater acidity, reflected by its pH value, is measured spectrophotometrically using m-cresol purple dye (mCP), as explained by Rérolle et al. (2012) and Liu et al. (2011). We choose this method instead of using pH electrodes due to its high precision (0.0005 unit pH) in saline water (Mosley et al. 2004). Since the pH change is very small during the acidification process, sometimes pH electrodes cannot detect the change, so a high precision method such as spectrophotometry is very essential for monitoring OA. In addition, the spectrophotometric method avoids common issues found in pH electrodes, such as a slow reading response (Whitfield et al. 1985), and the requirement of calibration for different samples with different ionic strengths (Millero 1986).

Total alkalinity is measured using the back titration method using strong acid (HCl) and strong base (NaOH) solutions (Grasshoff et al. 1999), while pCO₂ is measured underway using a Pro Oceanus Mini CO₂ sensor. On the other hand, water quality parameters including temperature and salinity are measured using a conductivity temperature depth sensor—SeaBird Electronic (CTD SBE) 19plus. Dissolved oxygen is measured using a DO meter Hanna HI 9146 while nutrients are measured spectrophotometrically using a continuous flow analyzer (Skalar SAN++).

Sampling frequency is essential in monitoring the dynamics of carbonate systems. Less frequent sampling may result in less accurate information on diurnal and seasonal carbonate system fluctuations, and subsequently hamper determining the lowest and the highest peak of the pattern. In addition, mean levels of carbonate system parameters in the observed location will not be accurately determined,

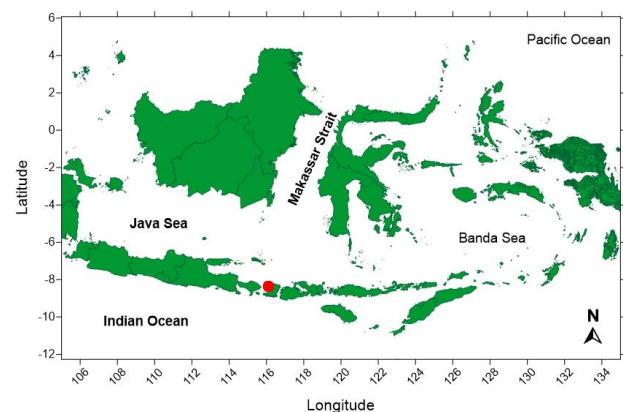


FIGURE 1. Pilot site for ocean acidification monitoring in the Lombok Strait, Indonesia (red dot).

as well. On the other hand, higher frequency sampling necessitates higher costs. Nonetheless, high frequency sampling is critical when initiating monitoring, especially when it is long-term. After accurate initial information on dynamic patterns is obtained, sampling frequency may be reduced to the point that sampling only covers critical points of common carbonate system fluctuation patterns over a specified timeframe in a particular location. For example, during a one-day observation, sampling is conducted at least at times when the lowest, the highest, and in-between level of carbonate system parameters are usually found.

In the first year of our monitoring, field sampling was conducted twice a year at different seasons, including the first transition (West to East) monsoon and second transition (East to West) monsoon. Sampling was conducted every three hours for two days (48 h) in each season. Sampling was not conducted at the other two seasons (West monsoon and East monsoon), since bad weather did not allow us to do sampling safely.

The biannual sampling experience in the first year resulted in a lot of information and new insight for the improvement of further monitoring. Such improvements can be applied to many aspects, including analysis instruments, analysis methods, sample treatments, and sampling frequency. Improvement in instrumentation can be done by utilizing advanced instrumentation such as an alkalinity automatic titrator to replace the conventional digital titrator and pH meter in measuring total alkalinity. In addition to saving time, the use of an automatic titrator may increase titration end point precision, which will result in better data acquisition. For the analysis method, an mCP dye solution must be made freshly every time spectrophotometric pH analysis is carried out. Storing the remaining dye solution for the next analysis on a different day must be avoided since the dye pH will change. Adjusting the dye pH to make it similar to the previous one will not bring the same ability of the dye solution to form color when reacting to samples.

In addition to the instrumentation and analysis method, improvements can be made to sample treatment in terms of the duration of sample storage. There was a slight difference in the result when analyzing carbonate system parameters for fresh samples compared with stored samples. Therefore, storing samples for a long time must be avoided. Lastly, sampling frequency must be extended. Since there are four seasons in Indonesia, sampling must be conducted at those four seasons to understand annual carbonate system variability between seasons. A well-planned strategy must be made to deal with safe sampling in the bad weather commonly found in West monsoon. Diurnal sampling must be extended, as well, from just two days to three or more days since the fluctuation magnitude and pattern of the carbonate system parameters differ with days.

Within the first two years of the monitoring plan, we only conducted the physical and biogeochemical monitoring of carbonate system variability. As for the biological parameters (i.e., CAU and ARMS), these will be deployed within the next term of monitoring activities. However, through the available secondary data, such as from the Coral Reef Rehabilitation and Monitoring Program - Coral Triangle Initiative (COREMAP-CTI), the biological data of the coral reef and seagrass ecosystems will be used as supporting data and information resources.

6. CONCLUSION

The ocean faces many threats as the result of high CO₂ emissions, among them being climate change and ocean

acidification (OA). The Indonesian seas will potentially become more severely impacted by both climate change and OA with time. Following up the SDG14, systematic research and monitoring of OA is essential. Conducting OA research and monitoring in Indonesia is quite challenging due to its large sea area with different water mass characteristics in different locations. However, we have to make the first initiative, i.e., by establishing a pilot site for OA monitoring. For this purpose, we have introduced an OA monitoring site in the island of Lombok and implemented systematic monitoring of biogeochemical parameters (carbonate systems) following the developed protocols. We expect that this initiative will be followed by other research entities to cover the representative area of Indonesian waters for OA research and monitoring.

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AUTHORS' CONTRIBUTIONS

HBP and AJW designed, conceptualized the study, and wrote the first draft of the manuscript. HBP contributed to the section of carbonate system variability and OA monitoring system. AJW contributed to the section of climate variability and the urgency of OA monitoring. SJ contributed to the biological aspect on OA monitoring. RM conducted analytical review and validation. All authors provided works of literature, conducted manuscript proofreading, and approved the final version of the manuscript.

COMPETING INTERESTS

The authors declare no competing interest.

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