Anticipating Ocean Deoxygenation in the Maritime Continent of Southeast Asia

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ABSTRACT Oxygen plays an essential role in the biogeochemical process and ocean productivity, especially during the recent trend of climate change. Development of the oxygen loss condition, deoxygenation, receives less attention than ocean acidification and warming. Therefore, understanding deoxygenation is indispensable. The maritime continent waters of Southeast Asia (SEA) are well-known for marine biodiversity and unique geological features. The area is inevitably impacted by climate change and will suffer more due to less oxygen in seawater. Based on previous research, Bengal Bay has been affected by oxygen depletion and climate change, in which hypoxic rate conditions continuously increase. In the other SEA area, seasonal hypoxia occurs in coastal areas as an impact of eutrophication. This occurs in Sanga Besar River Estuary, Bolinao and Anda coastal waters, Manila Bay, Jakarta Bay, and Cambodian waters. Deoxygenation anticipation is an essential step as a response to the development of oxygen loss areas, and monitoring is proposed as a preliminary step before the oxygen loss worsens. This review focuses on observing oxygen depletion changes and hypoxia in the maritime continent area, including its potency, effect, and recommendations on how to monitor deoxygenation.

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1. INTRODUCTION

The deficiency of global ocean dissolved oxygen (DO), known as deoxygenation, is a significant consequence of climate change (Levin 2018). Low oxygen conditions generally occur, ranging from hypoxia (<63 μM O2; <2mg O2/L; <1.4 ml O2/L) to anoxia (0 ml O2/L), and are expected to expand largely in the future (Middelburg and Levin 2009; Rudalca Baroni et al. 2020). This condition also shifts many sectors, such as circulation, nutrient input and release, various biogeochemical responses, and other forms of human distraction (Levin 2018). The dead zone, a popular term for oxygen depletion, affect the population decline of aerobic organisms (Diaz and Rosenberg 2008). Despite this condition, deoxygenation receives less attention than other climate change issues, such as ocean acidification and warming (Limburg et al. 2017). In the last 100 years, measuring oxygen change on a global ocean scale has been difficult (Limburg et al. 2017). There is little oxygenation research conducted that provides reliable data (Gilbert et al. 2009) and most oxygen changes are predicted from a model based on global warming stressors (Breitburg et al. 2018).

Southeast Asia (SEA) waters are located between two large basins, the Pacific and Indian Oceans, and two continents, Asia and Australia. These unique features are accompanied by marine and meteorological phenomena. For instance, the Indonesian Throughflow (Sprintall et al. 2019), as well as the South China Sea Throughflow (Wei et al. 2019), are responsible for the global heat and water transport from the Pacific to the Indian Ocean. On the other hand, the intra-seasonal to interannual variability timescale (e.g., Madden–Julian Oscillation, Kelvin waves, monsoon, Indian Ocean Dipole, ENSO) impacts regional weather systems (Loo et al. 2015; Sprintall et al. 2019; Wei et al. 2019). Between this unique climatological center of deep atmospheric convection, SEA also experiences variability in coastal and marine areas. SEA regions are known for their highly diverse and rich coastal marine ecosystems (Francisco 2016). These features include the complex movement of paleogeography (Hall 2009), which may form a restricted circulation area and hydrothermal activity of narrow ocean basin. These factors also develop different characteristics of oxygen properties. Despite its role in developing ocean zones, DO contributes to marine primary production (Levin 2018), such as, for example, upwelling along the south coast of Java. Nutrient-rich water rises toward the surface, initiating phytoplankton blooms (Sprintall et al. 2019). This productivity has a potential to increase oxygen consumption (Bakun et al. 2015). On the other hand, the development of the oxygen minimum zone (OMZ) in the northwest SEA region is a result of anthropogenic activity and seasonal variability (Bristow et al. 2017; Akester 2019).

SEA strongly influences changes in the climate and oceanic variability. At the same time, the global climate change brings anomalies to the SEA region, such as variability in rainfall and cyclonic patterns (Loo et al. 2015). Alteration in the monsoons has decreased precipitation by up to 70% from the average level (Loo et al. 2015), although in some areas topography also affects the intensity of rainfall. A shifting monsoon season is predicted to delay the onset of monsoons by 15 to 20 days in the future (Loo et al. 2015). It is thus proved that SEA marine and meteorological activities affect the condition of climate change.
The trend of ocean deoxygenation is increasing following ocean warming. Warmer seawater can release oxygen more easily than colder water, as warm water holds less dissolved oxygen. In some SEA areas, low oxygen conditions have already occurred, including in Hurun Bay (Santoso 2007), Sangga Besar River Estuary (Okamura et al. 2010), Bolinao and Anda coasts (Escobar et al. 2013), Manila Bay (Sotto et al. 2014; Vergara et al. 2017), Jakarta Bay (Ladwig et al. 2016), Cambodian waters (Burunaphatheprat et al. 2017), and Bengal Bay (Bristow et al. 2017; Kay et al. 2018; Akester 2019). Motivated by these trends, we summarize the oxygen depletion changes in SEA. This review article addresses deoxygenation conditions in SEA, their potential impact, and recommendations on deoxygenation monitoring as an initial systematic study on the deoxygenation issue in Indonesian and Southeast Asian waters.

2. OVERVIEW OF DEOXYGENATION

Low oxygen conditions occur naturally, but are impacted by human influences, or as a result between the interaction of natural and anthropogenic processes (Middelburg and Levin 2009; Wolanski and Elliott 2015; Levin 2018). Hypoxia decreases aerobic area and induces the mortality of many aerobic organisms. Based on Middelburg and Levin (2009), this condition is commonly found in (1) limited water flow areas of ocean basins and fjords, (2) natural intrusions or upwelling of hypoxic waters on shelf systems, and (3) coastal embayment of heterotrophic states from terrestrial and riverine organic matter. Human activity increasingly influences the establishment of multiple effects that include cultural eutrophication, river runoff, and ocean warming. The interactions of warming and nutrients influence the oxygen balance and DO dynamics in marine areas. When seawater temperature increases, oxygen solubility will decrease. Heat generates stratification in the water and wind patterns affect oxygen transport and mixing. On the other hand, high nutrient input may affect the large oxygen consumption of microbes.

Nitrogen (N) and phosphorus (P) production create a fundamental concept relating to dissolved inorganic nitrogen (DIN) consumption and primary production in space and time dimensions (Figure 1; Fennel and Testa 2019). High production of these nutrients and organic enrichment in the aquatic system contributes to the global proliferation of hypoxia and algal blooms (Korpin and Bonsdorff 2015). Increased exploitation of higher-level consumers with a combination of physical and geomorphological characteristics of waters is also a vital factor in the formation of the OMZ (Korpin and Bonsdorff 2015; Levin 2018). The dominant biogeochemical processes in this zone, which is the sulphur cycle, are particularly susceptible to oxygen, nitrate, and nitrite. Furthermore, pelagic euxinia from this cycle accelerates the depletion of nitrate and nitrite (Middelburg and Levin 2009; Sommer et al. 2016). This condition changes into high ammonium concentration, which is commonly found in low oxygen areas. Bacteria anaerobically produce N₂ gases from ammonium oxide. When these gases are released to the atmosphere, they will team up with other greenhouse gases (GHG) to make the Earth warmer.

On the other hand, P can quickly mobilize in the hypoxic condition, which significantly differs from nature of surface sediment as P burial sink (Conley et al. 2009). Together with iron, P generates enlargement of hypoxia (Ruvalcaba Baroni et al. 2020). This process completely changes the normal state, although during the nitrogen cycle, anaerobe condition is needed to ensure the ocean stays in oligotrophic conditions (Conley et al. 2009; Korpin and Bonsdorff 2015; Fu et al. 2018).

3. UNIQUE FEATURES OF OXYGEN DYNAMICS IN SOUTHEAST ASIA

Both the Indonesian Throughflow and South China Sea Throughflow contribute to freshwater and heat transports in SEA (Sprintall et al. 2019; Wei et al. 2019). According to Utamy et al. (2015) and Khadami and Suprijo (2019), interactions between the transport systems of the wind and the monsoonal climate of Southeastern Java induced upwelling. This activity increased ocean productivity along the southeastern coast of Java (Sprintall et al. 2019). Although it is still seen as a weak correlation, higher primary productivity occurs during east monsoon (EM) in June, July, and August. Moreover, upwelling activity intensified by a lower sea surface temperature (SST) and increased surface current coupled with strengthening of the Indonesian Throughflow prevailed during a strong EM in the ENSO 2015 period (Ahmad et al. 2019). Although hypoxia in southern Java is yet to be reported, upwelling from interactions with the wind facilitates hypoxic conditions (Feng et al. 2014).

Coastal hypoxia occurs seasonally in shallow depths where stratification did not occur as in deeper water (Santoso 2007; Ladwig et al. 2016). However, high stratification in deep water basins was also identified as anoxic when circulation is restricted. In 1988, east Indonesian basins with deep characteristics showed no anoxic conditions (Van Aken et al. 1988); however, recent studies have indicated their development into low oxygen basins (Murimoto 2016; Guistantini et al. 2018). In another SEA area, Bengal Bay is a naturally productive area that is indicated by upwelling activities. It reaches its peak in the dry season in April (Akester 2019). However, in the center area of Bengal Bay, a large and growing OMZ considered as persistent hypoxia was detected with a possibility of future nitrogen loss (Bristow et al. 2017; Akester 2019). That means the original Bengal Bay OMZ condition is different from other OMZ regions in terms of nitrogen depletion activities (Bristow et al. 2017), which impact its marine productivity (Kay et al. 2018).

Besides the OMZ in Bengal Bay, the evidence of oxygen depletion in SEA showed as a monsoonal period (Table I), where most of it occurred in aquaculture areas (Santoso 2007; Escobar et al. 2013; Sotto et al. 2014; Ladwig et al. 2016;

![Figure 1](image-url). Concept of primary production derived from dissolved inorganic nitrogen (DIN) limitation over space or time. Dashed (solid) lines indicate without (with) phosphorus limitation. DIN consumption becomes earlier and farther (slowly and farther) upstream (upstream), while PP in a smaller (border) area with higher (smaller) peak rates. Figure from Fennel and Testa (2019).
Takarina et al. (2017). Low DO activity was observed as hypoxia reoccurring periodically (Santoso 2007; Escobar et al. 2013; Sotto et al. 2014; Ladwig et al. 2016). In Pangasinan and Manila Bay, oxygen depletion occurs in June after algal blooms in the aquaculture area, due to the decomposition of organic matter (Escobar et al. 2013; Sotto et al. 2014). In Hurun Bay, hypoxia occurs in June–July due to the water intrusion of low oxygen seawater from the Java Sea (Santoso 2007). Hypoxic conditions have also occurred in Jakarta Bay with eutrophication increasing oxygen consumption of organic matter (Ladwig et al. 2016).

During seasonal hypoxic bottom conditions, water column stratification prevents DO diffusion (Sotto et al. 2014). Highly stratified water in Cambodian waters, caused by low surface salinity and subsurface warm water intrusion, generate low DO in near-bottom water (Buranapratheprat et al. 2017). As a consequence of oxygen exhaustion, hydrogen sulphide (H₂S) is produced and released from sediments. It is inferred from the dark color and strong H₂S odor that is responsible in nitrification process inhibition (Bordalo et al. 2016; Ladwig et al. 2016).

4. POTENTIAL IMPACT OF DEOXYGENATION

Climate change contributes to the unbalancing of the ocean biogeochemical system through intense algal blooms (Paerl et al. 2020). The oceanic climate cycle (namely ENSO) increases annual SST (Wang et al. 2017). A combination of warmer SST, anthropogenic nutrient loading, stratification, flow, and residence time will favor the dominance of cyanobacterial blooming (Paerl et al. 2020). This bloom has a significant consequence for a vast range organisms, including humans, because of its toxic substances and inducing of low oxygen concentrations (Paerl et al. 2020). Their incidence is predicted to increase due to climate change (Reichwaldt and Ghadouani 2012).

The combination of ocean oxygen loss and thermal stress has occurred in the past as evidence of climate change, such as at the end of the Permian Period (Penn et al. 2018). Triggered by volcanic GHG, hypoxia happened in the ocean. Low oxygen resulted in catastrophic mortality to aerobic organisms, but for some species, this event may be an advantage, especially for those that are invasive (Norkko et al. 2012; Bakun et al. 2015; Penn et al. 2018). This great dying concludes a future projection of ocean deoxygenation and warming, and also asserts the nature of marine living resources that depend on temperature and oxygen conditions (Penn et al. 2018).

Ocean warming as an effect of global climate makes oxygen less soluble in water, resulting in it holding fewer DO molecules (Keeling et al. 2010). One climate change model predicts that DO will decline by the year 2100 by approximately 1–7% within intermediate tropical water depths of 200–1000 m (Keeling et al. 2010). Based on Fu et al. (2018), the DO trend will reverse after 2150, with the increase in oxygen concentration and the shrinking of OMZ.

| Location                          | Year | Concentration (mg/L) | Method                                                                 | Reference         |
|-----------------------------------|------|----------------------|------------------------------------------------------------------------|-------------------|
| Indonesia Hurun Bay               | 2003 | <1                   | Sensor (Chlorotec Probe (Chlorotec, type AAQ1183, Alec Electronics)).  | Santoso (2007)    |
| Jakarta Bay                       | 2012 | 3.2–4.0              | Sensor (means of a CTD multiprobe measurements)                        | Ladwig et al. (2016) |
| Malaysia Sangga Besar River Estuary, Philippines | 2007 | <3                   | Sensor (DO meter (DKK- TOA, WQC-22A))                                | Okamura et al. (2010) |
| Boholano and Anda Coastal          | 2010 | <0.5                 | Sensor (YSI Sonde 650 MDS)                                            | Escobar et al. (2013) |
| Manila Bay                        | 2010 | 0.12–2.22            | Sensor (SEABIRD SBE-25 CTD and SEABIRD SBE-19 CTD)                    | Sotto et al. (2014) |
| Manila Bay                        | 2012 | 1.06–4.61            | Sensor (YSI MDS 6600 CTD)                                             | Vergara et al. (2017) |
| Thailand Bandon Bay                | 2002 | 3.06–5.80            | –                                                                     | Chumkiew et al. (2015) |
| Cambodia Mekong Delta              | 1998 | 2.0–3.8              | Sensor (YSI-Model 95 (YSI Environmental Corporation, Yellow Springs, OH, USA)) | Christensen et al. (2004) |
| Vietnam Vietnamese Waters          | 1999 | 1.862–4.788          | Sensor (Falmouth Integrated CTD instrument) + Winkler procedure for validating with oxygen sensor data | Rojana-Anawat et al. (2001) |
| South China Sea Basin              | 2001 | <2.128               | World Ocean Atlas 2001                                               | Li and Qu (2006)   |
| Vietnamese Coast                   | 2003 | 2.7–4.9              | Dissolved Oxygen Analyzer by SIS                                      | Dippner et al. (2007) |
| Myanmar Biskail Bay                | 2014 | 10 to 200 nM         | Sensor (STOX sensor (switchable trace oxygen))                        | Bristow et al. (2017) |
| Myanmar Biskail Bay                | 1990 | <0.665               | NOAA Hydrocasts (National Geophysical Data Center global hydrographic dataset of 20,260 hydrocasts) | Kay et al. (2018) |
| Bengal Bay                        | 2013 | 4.0–6.5              | Sensor (SBE-43 oxygen sensor) with validation with Winkler Titration  | Akester (2019)     |
volume. However, this recovery is unable to map the natural condition. The breakpoint should occur starting from a decrease in tropical biological export coupled with ventilation increases after 2200 (Fu et al. 2018).

Low oxygen prevention has the same principle as minimizing GHG emissions based on global climate change proposals. Despite the nutrient management plan that was proposed in Rabalais et al. (2007), increasing the density of macroalgae and seagrass habitats helps to maintain hypoxia stress in the surface sediment (Wahl et al. 2018). However, in the deep ocean layer, this solution faces different physical characteristics, among them low light.

5. MONITORING ON DEOXYGENATION

In many in situ observations, oxygen sensors are already provided in most instrument analyzers. This implies that DO is a critical constituent to characterizing and defining ocean conditions (Dave and Lozier 2013). Besides this measurement, many models have employed the determination of oxygen conditions, such as acoustic measurements (Peraltilla et al. 2017), as well as remote sensing. These findings should be verified using Winkler titration. Even though this method is not convenient, it is nonetheless very reliable (DiMarco et al. 2012).

Based on the literature (Table 1), many direct DO measurements use a sensor in a multi-parameter, for instance, YSI Sonde 650 MDS (Jacinto et al. 2011), real-time analysis with CTD, such as the SBE43 DO Sensor on Seabird 911 CTD (DiMarco et al. 2012), and Argo free-drifting profiling floats (Gruber et al. 2010). The real-time DO measurement in the CTD system is integrated with a Niskin bottle deployed with a winch, then gathers water and data based on the depth setting (DiMarco et al. 2012). Probes of the analyzer immediately dip in water to measure DO content. Real-time DO data obtained from a sensor (Jacinto et al. 2011; DiMarco et al. 2012), along with DO data verification use water from a Niskin bottle. Meanwhile, Winkler titration is performed to make sure oxygen data are genuine, authentic, and accurate.

Stable isotopes are applied to the measurement the development of hypoxia in water. Lehmann et al. (2009) determined respiration rates with stable oxygen isotopes from the surface to the deep layer, with the assumption that DO is continuously consumed at deep, landward water layers. This research also explained sediment oxygen demand in the hypoxic area of Lower St. Lawrence Estuary. However, Bourgault et al. (2012) observed that hypoxia on the 100 m thick bottom layer characterized from pelagic oxygen demand needs to be five times higher than sediment oxygen demand. This recent research reveals that stratification in the hypoxic area impacts the lower bottom layers.

Acoustic technology, as the latest technology in oceanography, provides tools to monitor the OMZ, and such an observation was published by Peraltilla et al. (2017). OMZ characteristics obtained from an echo sounder were then calculated using the Echoview software algorithm. This technology can be useful for long term fleet monitoring; however, the coverage of data is obtained from the site sounded by the echo sounder.

The measurement of water stratification provides a useful indicator of deoxygenation. Based on Behrenfeld et al. (2006), satellite measurements of ocean color, SeaWiFS, give an estimation of ocean productivity—net primary production and linking its variability to environmental factors—the Multivariate ENSO Index (MEI). These data provide researchers with the ability to confirm hypoxic or anoxic conditions. Every measurement method or tool has its drawbacks and advantages.

6. CONCLUSION

The development of low oxygen conditions, or deoxygenation, is already occurring in Southeast Asia, including seasonal and persistent hypoxia. Deoxygenation shifts the biogeochemical cycle, ocean stratification zone, aerobic organism populations, and GHG in the atmosphere. In some areas of SEA waters, seasonal hypoxic areas have already been detected, such as Hurun Bay, Sangga Besar River Estuary, Bolinao and Anda coasts, Manila Bay, Jakarta Bay, and Cambodian waters. A persistent OMZ has already formed in Bengal Bay. The anticipation of deoxygenation stars from nutrient management plants that effectively reduce hypoxia on coasts. Measuring hypoxia activity is formed from a conventional method based on Winkler titration, CTD real-time measurement, and using more recent technology, such as acoustics and satellites, to provide advanced tools in the observation of deoxygenation.

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AUTHORS’ CONTRIBUTIONS

IW initiated the first draft of the manuscript and provided the literature search. AJW contributed to the study framework. KT contributed on section and storyline continuity. All authors conducted manuscript proofreading and approved the final version of the manuscript.

COMPETING INTERESTS

The authors declare no competing interest.

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