Deoxygenation of the eastern Indonesian waters and its variability

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Abstract. Long-term ocean deoxygenation could lead to decline biological productivity and alter biogeochemical cycles. Ocean warming contributions to ocean deoxygenation are reasonably understood, however, there is a challenge to reveal the gaps about other modifying factors to explain different regional patterns and predicts the condition in the coming century. This study aimed to identify the deoxygenation areas in the eastern Indonesian waters, understand the variability of physical and chemical parameters as the deoxygenation drivers, and investigate the correlation between parameters. In-situ and satellite-derived data from 1995 to 2020 were analyzed with statistical methods and remote sensing techniques to enhance deoxygenation measures in higher spatial and temporal resolutions. Our findings revealed that significant deoxygenation was detected around the Arafura Sea. The oxygen minimum zone extended at 133.5° – 136.8° E in the depth of 350 – 1,000 meters, with less than 2 mmol/m³ of dissolved oxygen concentration. Nitrate, phosphate, and temperature were identified to have a strong reversed relationship with the oxygen concentration in the study area. This study also developed multiple regression model algorithms to estimate the oxygen concentration in specified depths.

Keywords: Deoxygenation, eastern Indonesia, oxygen minimum zone, remote sensing

1. Introduction

Oxygen loss in the open ocean (ocean deoxygenation), is well documented but continues to occur in many regions. The world ocean has lost ~2% of its oxygen content but appears worse in the North Pacific, Southern Ocean, and tropical ocean regions [1, 2]. Ocean deoxygenation is understood to be a major consequence of climate change from the effects of global warming and exacerbated by increased anthropogenic nutrient loading and various biogeochemical feedbacks [3, 4]. The long-term oxygen reduction is proven to have notable impacts, such as reducing biological productivity and diversity and altering biogeochemical cycles [5, 6]. One of the most significant consequences of ocean deoxygenation is the area and volume expansion of the Oxygen Minimum Zone (OMZ). OMZ defined here is a region of the ocean where the oxygen concentration is lower than 22 µmol/kg, usually within depths of 100–1,200 m [7]. The oxygen levels in the OMZ are too low to support the living things and affect crucial components of the biological pump [8-10].
In the last decade, long-term deoxygenation observations have been integrated into regional and global synthesis to raise awareness of the phenomenon [7]. However, ocean deoxygenation is a complex product of physical, biological, and chemical drivers, some of which remain poorly understood. There is a challenge to reveal the gaps about other modifying factors besides ocean warming to explain different regional patterns and predict the condition in the coming century. Models and forecasts from many disciplines will be needed to develop a deeper understanding of processes controlling ocean deoxygenation [11]. Nowadays, satellite remote sensing data is more frequently applied in water quality studies [12, 13]. The satellite data provide extended temporal frequency and spatial coverage with better resolution than single in-situ measurement [13, 14]. Nevertheless, in-situ measurement data is still needed to validate the accuracy and reliability of remotely sensed data. The combined in-situ and satellite data analysis will be advantageous to monitor ocean deoxygenation in medium spatial and temporal resolution.

Eastern Indonesian waters, which represent the climate-regulated tropical marine region, were chosen as the locus area in this study. This region was suspected to experience significant ocean deoxygenation in the last decades. Physical and chemical data of the eastern Indonesian waters collected from in-situ and satellite sources from 1995 to 2020 were investigated and statistically analyzed. The aims of this study were to identify the deoxygenation areas in the eastern Indonesian waters, understand the variability of physical and chemical parameters as the deoxygenation drivers, and investigate the correlation between parameters. Multiple regression models of oceanic parameters were also developed to estimate the oxygen concentration in various depths. The study results were expected to provide scientific information as an initial step in supporting climate change mitigation and adaptation measures.

2. Materials and Methods

2.1. Study area

The study area was a climate-regulated marine region situated in the eastern Indonesian waters, located at 120⁰ – 140⁰ E and 0⁰ – 12⁰ S between Indonesia’s big islands of Celebes and Papua (Figure 1). This region is a complex marine system consisting of Molucca Sea, Halmahera Sea, and Ceram Sea in the northern area, Pacific Ocean and Arafura Sea in the eastern area, Timor Sea and Indian Ocean in the southern area, and Flores Sea and Savu Sea in the western area. The area crossed by A – A’ vertical depth section, along the Flores – Banda – Arafura Seas, is strongly influenced by seasonal upwelling and plays a crucial role in supplying upwelled nutrient-rich water that contributes to high marine primary productivity [15]. The Arafura Sea in the eastern area is a relatively shallow water basin (< 200 m) affected by monsoonal winds and the Banda Sea circulation [16]. Meanwhile, the Banda Sea is the largest and deepest ocean basin of the Indonesian Seas, which has a longer upwelling duration than other waters in Indonesia [17, 18]. The vertical section also crosses the confluent reservoir of the Indonesian Throughflow (ITF) that carries massive volume and heat from the Pacific to the Indian Ocean [19].

2.2. Satellite data

There were 6 (six) physical and chemical parameters derived from reanalysis and forecast models of satellite remote sensing data. These models were through processing level four (L4) and provided by E.U. Copernicus Marine Service Information in NetCDF-4 data format. The physical parameters consisted of potential temperature (T) and salinity (S) data, retrieved from reanalysis model of ‘Global Ocean Physics Reanalysis’ for the period of January 1995 to December 2019 and real-time forecast model of ‘Global Ocean 1/12’ Physics Analysis and Forecast Updated Daily’ for the period of January 2020 to December 2021. The chemical parameters consisted of dissolved oxygen (O₂), nitrate (NO₃), phosphate (PO₄), and dissolved silicate (SiO₂) data, retrieved from reanalysis model of ‘Global Ocean Biogeochemistry Hindcast’ for the period of January 1995 to December 2019 and real-time forecast model of ‘Global Ocean Biogeochemistry Analysis and Forecast’ for the period of January 2020 to December 2021. The temporal resolution of the models was monthly mean and the spatial resolution...
was 9.21x9.21 km for physical data and 27.75x27.75 km for chemical data with vertical coverage up to 5,500 meters depth.

![Figure 1](image.png)

**Figure 1.** The study location map of the eastern Indonesian waters, in-situ data locations were symbolized by the red dots.

2.3. **In-situ data**

In-situ data of this study were collected from the World Ocean Database ver.18 (WOD18) provided by National Centers for Environmental Information (NCEI), National Oceanic and Atmospheric Administration (NOAA). WOD18 has been archiving ocean profiles from around the world from the 1800s until 2018. The in-situ data locations were presented in Figure 1 and symbolized by red dots. In these locations, continuous ocean profiles measurements were conducted by Indonesian and Australian research cruises and projects and archived by WOD18. The WOD18 data were retrieved by Conductivity-Temperature-Depth (CTD) and Ocean Station Data (OSD) instrument supported with quality control flags associated with the automatic checks system. Nevertheless, we only collected similar parameters that ranged in our chosen period.

2.4. **Data processing and analysis**

To quantitatively evaluate the trends and the spatial-temporal variability of the ocean deoxygenation in the eastern Indonesian waters, the monthly average values of satellite data in the depths of 0, 100, 250, 500, 1,000, and 2,000 meters were extracted and visualized in charts and maps. The first step in data analysis was to validate the reliability of remote sensing data. We compared the extracted matching
values of the remote sensing and in-situ datasets in the same periods, locations, and depths. A matching value was based on the closest 3 x 3 satellite pixel values to the in-situ measurement location within a one-day time interval. The pairs were valid if at least 6 of 9 satellite pixels were available and the average difference between the central pixel and all other pixels was less than 25%. Afterward, we conducted the calculations of coefficient determination or R square (R²) and Mean Absolute Deviation (MAD) to the pairs to know whether the satellite datasets were reliable to use in the entire analysis, and also Root Mean Square Error (RMSE) and Mean Absolute Percentage Error (MAPE) to provide information on how much the satellite value error in predict the in-situ value [20, 21].

The seasonal analysis was interpreted from the surface data and the vertical section charts. Statistical analysis of Pearson Product-Moment Correlation was performed to find the correlation or relationship between parameters. The Multiple Linear Regression analysis was performed to identify the most influential parameter on dissolved oxygen variability and to develop algorithms to estimate dissolved oxygen concentration in specified depths. All satellite data processing in this study were using QGIS ver.3.16 software, the in-situ data were processed using Ocean Data View ver.5.4.0 software, and statistical analyses were performed using R ver.3.6.1 software.

3. Results and Discussion

3.1. Satellite data validation

There were 327 in-situ data values having the complete six parameters that were available in 1995 – 2020 ranging from the depths of 0 to 2,000 meters. However, only 100 matching pairs passed the matching value procedures. The validation of these matching pairs on each parameter showed the R² of 0.95, 0.96, 0.90, 0.99, 0.95, and 0.91 for oxygen, temperature, salinity, nitrate, phosphate, and silicate, respectively. Regarding the remote sensing-based models experimental for water quality parameters by [22], these determination coefficients indicated that the satellite data were reliable to be applied in the entire analysis. Figure 2 showed the comparison of in-situ and satellite-derived parameters in the eastern Indonesian waters. The figure showed log-linear relationships between in-situ and satellite-derived parameters as proven by the very high R² value for each parameter. Table 1 summarized the error statistics for data sets presented in this study. Based on prediction error testing conducted on satellite data towards in-situ data, the biases shown in RMSE were relatively small, and the average MAPE of the six parameters was 9.87%, assumed coherent because not exceeding 10% of the error margin [21].

| Parameters | R²  | MAD  | RMSE | MAPE (%) |
|------------|-----|------|------|----------|
| O₂         | 0.95| 12.40| 13.44| 9.41     |
| T          | 0.96| 1.39 | 1.80 | 12.71    |
| S          | 0.90| 0.30 | 0.33 | 0.87     |
| NO₃        | 0.99| 1.42 | 2.01 | 14.85    |
| PO₄        | 0.95| 0.26 | 0.29 | 11.04    |
| SiO₄       | 0.91| 9.74 | 13.91| 10.32    |
Figure 2. Comparison of satellite-derived and in-situ oxygen (a), temperature (b), salinity (c), nitrate (d), phosphate (e), and dissolved silicate (f) in the eastern Indonesia waters.

3.2. Seasonal patterns of the surface waters
Figure 3 showed the trends of surface oxygen and temperature in the eastern Indonesian waters from 1995 – 2020, based on the monthly concentrations of the two parameters. In general, there was a decreasing trend in surface oxygen (indicating surface deoxygenation) and increasing surface temperature over decades. The average concentration of surface oxygen during 25 years was 201.41 ± 2.56 µmol/kg, with the highest peak found on August 1996 (207.09 µmol/kg) and the lowest point in March 2016 (197.01 µmol/kg). A negative correlation can be visually interpreted in the graph, where the surface oxygen will reach the highest value when the surface temperature was in the lowest state. Seasonally, surface oxygen increased during the southeast (SE) monsoon (July-August-September) and decreased during the northwest (NW) monsoon (January-February-March). These patterns coincide with upwelling events of the eastern Indonesian water during the SE monsoon, which causes reduced heat at the sea surface and subsurface to reach minimum values [15, 17].

There were indications of significant decreases in surface oxygen concentration in 1998, 2010, and 2016 (shown by gray shade in Figure 3). In these years, the annual highs for surface oxygen were much lower than in other years, coincide with higher annual lows for surface temperature compared to other years. According to the El Niño Southern Oscillation Index (SOI) and Indian Ocean Dipole (IOD) index [23, 24], surface oxygen decreases in the eastern Indonesian waters occurred during strong ENSO of El Niño with positive IOD events in 1997 – 1998 and 2015 – 2016, and La Niña with negative IOD events in 2010 – 2011. Due to the unavailability of supporting data, the relationship between the deoxygenation of eastern Indonesian waters with ENSO–IOD events will not be discussed in this study.
3.3. The extension and the variability of the deoxygenation

The OMZs caused by deoxygenation in the world seas formed either naturally or anthropogenically [4]. The naturally-formed OMZs, where the physical and biogeochemical processes reduce the low concentrations of oxygen, are generally located in offshore regions, while the anthropogenically-formed OMZs, where eutrophication is the primary cause, mainly occurred in the coastal regions [4, 25]. We identified the surrounding areas of the Arafura Sea, located between 130° – 137° E, are experiencing deoxygenation for over 25 years (Figure 4). Low oxygen concentrations of 10 – 20 µmol/kg were found in 2020 at 350 – 1,000 meters depth at 133.5° – 136.8° E (Figure 4). The oxygen concentration in the core OMZ decreased from 76 µmol/kg in 1995 to 10 µmol/kg in 2020, which means that the deoxygenation rate in OMZ is ~2.6 µmol/kg/annual, and if it continues, the OMZ will go anoxic in less than five years. The similar low oxygen levels were also found in other tropical marine OMZs, such as in the tropical North Atlantic (15 µmol/kg) [8], tropical North Pacific (5 µmol/kg) [26], Arabian Sea (5 µmol/kg) [27, 4], and Bay of Bengal (0.5 µmol/kg) [28], located at the mid-depths of the water columns.

Seasonal patterns of deoxygenation in the eastern Indonesian waters were characterized by the monsoonal winds and the upwelling events. Figure 4 showed the upper ocean movements caused by the monsoonal winds that blow eastward in the NW monsoon and westward in the SE monsoon. The upwelling event of the Indonesian seas occurred in the SE monsoon and characterized by the upward movement of deep waters shown in Figure 4, which replace nutrient-depleted surface waters. The vertical mixing from the deep sea to the continental shelf helps phytoplankton blooms and replenish the surface water nutrients that already high due to the massive river discharge [15, 16].

Figure 5 showed the changes in temperature, salinity, nitrate, phosphate, and silicate from 1995 to 2020 in the eastern Indonesian waters. There was no visually significant long-term change of temperatures in the eastern Indonesian waters, except for the slightly rising temperatures in the upper ocean. However, a distinct increase of salinity was identified in 2020, located in the surrounding Arafura Sea at 400 – 1,000 meters depth. Figure 5 also showed the association of the temperature increases in the upper ocean with the decrease of nutrients. Nutrients are depleted in the surface waters through uptake by phytoplankton, and with increasing depth, nutrients sink its remaining skeletal and stratified in the water column [6]. Nitrate and phosphate concentrations were elevated (up to 40 mmol/m³ and 2.75 mmol/m³ for nitrate and phosphate, respectively) approximately at 700 – 1,700 meters depth with a longer vertical extension around the Arafura Sea. Meanwhile, silicate concentrations were increased laterally with depths up to 140 mmol/m³ at 2,000 meters depth. The increased nutrient stratifications result in reduced ventilation in the water columns and the OMZs [8].
We suggest the terrestrial inputs from the coastal regions surrounding the Arafura Sea also contribute to the deoxygenation and OMZ because of the high nutrient concentration stratified in the water columns. The directions of the long-term elevated nutrient concentrations were also suspected of coming from the coastal area of the Arafura Sea. The mountainous Papua Island along the northern and eastern boundaries of the Arafura Sea is a significant source of freshwater (1,175 km$^3$/year) and sediment (571 Mt/year) supply [29]. The terrestrial inputs from this region are heavily impacted by mining and unregulated land activities and aggravated by sediments derived primarily from landslides, channel erosion, and hillslopes erosion. The steep topography of Papua catchments leads to an intense discharge with carbon, nitrogen, and phosphorus rates that are much higher than those from other tropical coastal worldwide [29].

3.4. Significant correlation between the oceanic parameters

The relationship between dissolved oxygen and other parameters, identified by the Pearson Product-Moment Correlation, were shown in Figure 6. The correlation analysis included all satellite-derived and in-situ data, gathered from 1995 to 2020 with a total of 572 datasets, and grouped based on the depths from 0 to 2,000 meters. Generally, dissolved oxygen tends to correlate negatively with temperature, salinity, nitrate, phosphate, and silicate in all depth groups, except in the surface waters. The relationships were stronger at the depths of 500, 250, and 100 meters (Pearson correlation is between -0.5 and -1), especially for nitrate and phosphate that showed very close to the maximum negative value (-1). The negative signs on the values indicated reverse relationships between oxygen concentration with other parameters. This was means that the oxygen concentration on the waters will decline if the temperature, nitrate, silicate, phosphate, and salinity level increase.

We also analyzed how much the temperature, salinity, nitrate, phosphate, and silicate were individually able to explain the oxygen concentration variability by calculating the coefficients of determination ($R^2$). The results showed that nitrate individually has the greatest influence on oxygen concentration in the eastern Indonesian waters by 82.8%, followed by phosphate, temperature, silicate, and salinity by 80.4%, 73.9%, 39.7%, and 14.8%, respectively. However, the effect of the highest three parameters on oxygen concentration becomes greater when they were combined. The combination
influence from nitrate, phosphate, and temperature affects oxygen concentration by 87.6%, greater than the individual effect from each parameter. The test proves that nitrate, phosphate, and temperature parameters contribute significantly to explaining oxygen concentration variability in the eastern Indonesian waters.

**Figure 5.** Changes in temperature (a), salinity (b), nitrate (c), phosphate (d), and silicate (e) concentrations in the eastern Indonesian waters over 25 years.
Figure 6. Pearson Product-Moment Correlation between dissolved oxygen with temperature, salinity, nitrate, phosphate, and silicate in the eastern Indonesian waters in different groups of depth.

Because the temperature, salinity, nitrate, phosphate, and silicate concentrations will eventually change over time, we should expect significant changes in oxygen concentration in the future that may cause the extensive impact of deoxygenation. The 5 (five) satellite-derived parameters were used to estimate in-situ oxygen concentration in specified depths of the eastern Indonesian waters by applying the multiple regression analyses. We developed models with the highest determination coefficients and free multicollinearity issues by inputting the parameters with the stepwise method. The empirical algorithms of the models can be derived as:

\[ O_{20} = 274.24 - 1.99 \cdot T - 0.48 \cdot S - 1.57 \cdot NO_3 + 1.29 \cdot PO_4 + 0.03 \cdot SiO_4 \]  
\[ O_{2100} = 226.73 - 0.45 \cdot T - 0.70 \cdot S - 12.30 \cdot NO_3 + 43.60 \cdot PO_4 + 4.54 \cdot SiO_4 \]  
\[ O_{2250} = 542.02 - 5.15 \cdot T - 4.36 \cdot S - 0.46 \cdot NO_3 - 137.32 \cdot PO_4 + 0.65 \cdot SiO_4 \]  
\[ O_{2500} = -183.41 - 2.69 \cdot T + 16.48 \cdot S - 3.00 \cdot NO_3 - 56.34 \cdot PO_4 - 0.83 \cdot SiO_4 \]  
\[ O_{21000} = 1.691.85 - 7.08 \cdot T - 31.04 \cdot S + 1.42 \cdot NO_3 - 150.20 \cdot PO_4 - 1.40 \cdot SiO_4 \]  
\[ O_{22000} = -2.834.84 - 2.36 \cdot T + 100.14 \cdot S - 0.92 \cdot NO_3 + 6.79 \cdot PO_4 - 3.81 \cdot SiO_4 \]

Where \( O_{20} \) is estimated oxygen concentration on the surface (\( R^2 = 0.65 \)), \( O_{2100} \) is estimated oxygen concentration on the depth of 100 m (\( R^2 = 0.98 \)), \( O_{2250} \) is estimated oxygen concentration on the depth of 250 m (\( R^2 = 0.94 \)), and \( O_{2500} \) is estimated oxygen concentration on the depth of 500 m (\( R^2 = 0.99 \)), \( O_{21000} \) is estimated oxygen concentration on the depth of 1,000 m (\( R^2 = 0.86 \)), and \( O_{22000} \) is estimated oxygen concentration on the depth of 2,000 m (\( R^2 = 0.68 \)). By using the satellite-derived algorithms, long-term changes in oxygen concentration of the eastern Indonesian waters can be detected with limited direct observation data.
4. Conclusion
In the present study, we analyzed in-situ and satellite-derived data collected from 1995 to 2020 to understand the deoxygenation in the eastern Indonesian waters. A west-east vertical section extending from 120° to 138.5° E along 7° S was observed to investigate the variability in dissolved oxygen, temperature, salinity, nitrate, phosphate, and dissolved silicate parameters. Our analyses show the overall decreasing trend of surface oxygen with significant decreases in 1998, 2010, and 2016. Monsoonal winds and upwelling events strongly affect the seasonal variability of surface oxygen and temperature. Surface oxygen will reach the highest peak in the SE monsoon when the surface temperature is in the lowest state and vice versa. OMZ was well defined in 2020, which previously did not exist in 1995, located at 133.5° – 136.8° E with low oxygen concentrations of 10 – 20 µmol/kg in the depth of 350 – 1,000 meters.

We suggest the terrestrial inputs from the coastal regions surrounding the Arafura Sea also contribute to the deoxygenation and OMZ because the high nutrient concentration in the water columns suspected comes from the coastal area, which having an intense discharge of carbon, nitrogen, and phosphorus. Generally, dissolved oxygen correlates negatively with temperature, salinity, nitrate, phosphate, and silicate in all depth groups, except in the surface waters. The reversed relationships are stronger at the depths of 500, 250, and 100 meters. Statistically, nitrate has the greatest individual influence on oxygen concentration in the eastern Indonesian waters, followed by phosphate and temperature. However, the influence of these three parameters becomes greater when combined. Multiple regression models were developed to estimate in-situ oxygen concentration in specified depths. Additional works and tests, such as in-depth analyses of the underlying physical and biogeochemical processes, would be necessary to improve the model performances in simulating future oxygen changes in broader regions.

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