Impact of ENSO and IOD on chlorophyll-a concentration and sea surface temperature in the Bali Strait

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Abstract. ENSO and IOD are oceanographic phenomena that occur in the tropical Pacific Ocean and Indian Ocean, due to the interaction between the sea and the atmosphere. The study aims to determine the impact of ENSO and IOD on the abundance of Sea Surface Chlorophyll (SSC) and Sea Surface Temperature (SST) in the Bali Strait. The data used are Ocean Nino Index (ONI), Dipole Mode Index (DMI), Sea Surface Chlorophyll (SSC) and Sea Surface Temperature (SST). The method applied the SSC and SST anomaly analysis during the ENSO and IOD periods from March 2000 to July 2020. The results showed that during the ENSO and IOD periods in the eastern monsoon, there was an increase in SSC concentrations and a decrease in SST in the Bali Strait. In the ENSO period, there were La Nina and El Nino phases, while IOD had positive and negative phases. During the observation, it was known that the mean range of SSC was 0.49 - 1.91 mg m$^{-3}$ and 25.32 - 29.30 °C for SST. SSC anomaly during the observation period was between -0.04 - 0.62 and SST was -0.66 - 1.47. Therefore, it was known that the period that causes an increase in high SSC and a decrease in SST in the waters of the Bali Strait was during the El Niño period along with positive IOD phases in 2006, 2015, 2018, and 2019.

1. Introduction
The Bali Strait separates the two main islands, namely Java and Bali. The waters of the Bali Strait connect the sea water mass in the Bali Sea to the Indian Ocean or vice versa. So that the characteristics of the water mass in the Bali Strait are quite unique and dynamic. Apart from its geographical location, the Bali Strait is influenced by local, regional and global phenomena. Phenomena that occur from the interaction of the oceans and the atmosphere, such as Monsoon, Indian Ocean Dipole (IOD) and El Nino Southern Oscillation (ENSO). ENSO is an oceanographic phenomenon that occurs in the tropical Pacific Ocean, while IOD is an oceanographic phenomenon that occurs in the Indian Ocean. ENSO and IOD cause changes in regional and global climate variability that lead to various natural disasters such as floods, drought, ecosystem damage, cyclones, agriculture, and fisheries [1]. Monsoon is the movement of the wind from the continent of Australia to Asia. The monsoon wind system, which changes with the seasons, results in seasonal and annual variability in the waters. During the southeast monsoon (June-September) the movement of surface water masses tends to westward. This condition affects the characteristics of the water mass in the subsurface rising to the surface and has an impact on water fertility [2, 3]. Research on the impact of ENSO and IOD phenomena on oceanographic conditions, especially the abundance of Sea Surface Temperature (SST) and Sea Surface Chlorophyll (SSC) in
Indonesian waters is still minimal, especially in the strait area. Several studies that have conducted research on the effect of ENSO and IOD on upwelling in Southern Java waters include [4-8].

Chlorophyll-a is an important element in the formation of primary producers in aquatic environments, and SST is an important element in the process of absorption of sunlight. SSC and SST have an important role in the absorption and release of CO2 in the atmosphere through photosynthesis. The waters of the Bali Strait have high SSC concentration variability due to the upwelling process. Upwelling locations are known to have very high fishery potential. This study aims to determine the impact of ENSO and IOD on the abundance of SSC and the dynamics of SST in the Bali Strait.

2. Method

2.1. Study Area

The research location was in the waters of the Bali Strait (Figure 1). Bali and Java (Indonesia) are separated by the Bali Strait, a narrow stretch of water only 3 km across. The temperature of the water in Bali Strait is prone to major seasonal fluctuations, predetermined by means of the periods of monsoons. During the period of the north western monsoon (January–March), average temperature is about 28-29 °C, whereas in the southeast (July–September) temperature decreases to 26 °C. Regardless of the season, the water temperature in the northern part of the strait is 1-1.5 °C lower than it is in the southern part.

![Figure 1. Map of study area](image)

2.2. Dataset

This research was applied 20 time series data of oceanographic parameters, includes March 2000 to July 2020. The data used are composite image data from the Aqua/Terra MODIS Level-2 satellite with a spatial resolution of 1 km and daily temporal resolution. Composite data from the daily Aqua/Terra
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Satellites is made monthly averaged from March 2000 to July 2020. Data obtained from the page https://oceancolor.gsfc.nasa.gov/. This image data is used to obtain information on the distribution of SST and SSC in the Bali Strait. Furthermore, the image data was analysed using SeaWiFS Data Analysis System (SeaDAS) version 7.5.3 based on LINUX software using MODIS Theoretical Basic Documents Algorithm to show SST and SSC values.

Moreover, Ocean Nino Index (ONI) is an index generated from observations of ocean and atmosphere interactions in the Tropical Pacific Ocean which can be identified from the NINO 3.4 region at coordinates 120°-170° W and 5° N - 5° S [6]. The ENSO index refers to observations from the NOAA Climate Prediction Center which can be downloaded on the https://stateoftheocean.osmc.noaa.gov/sur/pac/oni.php. While the IOD index is an index generated from observations of ocean and atmosphere interactions in the Indian Ocean Trophies identified from the western equatorial Indian Ocean (50° - 70° E and 10° S - 10° N) and the south eastern equatorial Indian Ocean (90°-110° E and 10° S - 0°/Equatorial) [9]. The IOD index refers to the results of observations made by NOAA which can be downloaded on the https://stateoftheocean.osmc.noaa.gov/sur/ind/dmi.php.

2.3. Data Analysis

2.3.1. Anomaly Analysis
As an effort to avoid the erroneous estimation of SSC data from the impact of suspended particles, baseline reflectance, and case-2 water conditions, SSC data in the range 0 < SSC < 5 mg.m-3 were used. For SST data, filtering was carried out in the range 23 < SST < 33° C. The temperature range is based on several previous field measurements, where the value has never exceeded the selected range. Analysis of variability using SST and SSC anomalies approach [10]. Anomaly is calculated by Xi – X, where Xi is SST or SSC of the monthly Aqua/Terra MODIS satellite imagery in i-month, and X is the monthly average of data for the period March 2000 - July 2020.

SST was obtained using MODIS Theoretical Basic Documents Algorithm (ATBD MOD 25) [11]. SSC data were collected also from Aqua/Terra satellite imagery with the MODIS sensor, monthly composite, and in 1 km of spatial resolution, and were obtained using the Theoretical Basic Documents MODIS Algorithm (ATBD MOD 19) [12].

2.3.2. Hovmoller Diagram
The spatial analysis of time series data along latitude or longitude uses the Hovmoller diagram. This diagram is to study the SST and SSC variations in the longitude or latitude coordinates of each month during the observation time in the study area. The data is displayed crosswise against the SST and SSC anomaly data which represents the numerical pixel value of the time series data. The use of this diagram is to describe phenomena that change with duration of time.

3. Result and Discussion

3.1. Sea Surfaces Temperature and Chlorophyll Variability
The monthly variation in SSC and SST in the waters of the Bali Strait is presented in Figure 2. The monthly variations of SSC have an annual cycle, and experienced a significant dynamic in April until August, then decreased starting from September. As for SST, the process is the opposite. The maximum chlorophyll-a concentration occurred in August which reached 1.79 mg.m-3 with the lowest SST of 25.32 °C. So that this water area is interesting to study due to spatial and temporal variability that is clearly visible from the distribution of chlorophyll-a and sea surface temperature. The composition of chlorophyll-a distribution in the west monsoon period (DJF) was around 0.37 mg.m-3, and the west to east monsoon (MAM) was 0.56 mg.m-3.

In the eastern monsoon (JJA) the SSC increased to 1.29 mg.m-3 and in the east to west transition monsoon (SON) to 1.14 mg.m-3. During the eastern monsoon (JJA) and transition (SON) SSC were
high and spread in almost all waters of the Bali Strait. Meanwhile, SST conditions in the west monsoon period (DJF) were around 29.23 °C and in the transitional monsoon (MAM) 29.02 °C. In the east monsoon (JJA) SST has decreased by around 26.51 °C, and begins to increase in temperature in the transitional period (SON) of 27.18 °C. The condition of low SST in the eastern monsoon (JJA) with an abundance of SSC in almost all area of the Bali Strait. This condition is an indication of upwelling. Meanwhile, in the west season (DJF) the abundance of SSC tends to decrease and the SST increases. This condition is due to the downwelling process in the waters of the Bali Strait.

Figure 2. (a-d) Average of SST and (e-h) SSC in DJF, MAM, JJA, and SON periods in Bali Strait.

3.2. ENSO and IOD on Sea Surfaces Temperature and Chlorophyll Anomaly

Interannual climate variability (ENSO and IOD) affects the distribution of SST and SSC in Indonesian waters. Figure 3 shows the temporal variation of SST and SSC in the Bali Strait associated with the
presence of ENSO and IOD phenomena. In the La Nina period (2000 and 2007), SSC were seen to increase at the end of the MAM transition season, namely in May and the peak occurred during the transition season of SON which peaks in October. In contrast, during the El Nino (2002, 2004, and 2009) SSC began to increase in May to October and in November began to decline.

During the IOD (+) period (2003 and 2012) there was an increase in SSC starting from May to October with the peak occurring in August. During the IOD (-) period (2001 and 2013) the concentration of chlorophyll-a began to increase from May to September and in October began to decline. The combined period of El Nino and IOD (+) (2006, 2015, 2018 and 2019) described SSC began to increase in May to September and in October began to decline. Moreover, the combined period of La Nina and IOD (+) (2008, 2011, and 2016) showed SSC began to increase in May to September and in October began to decline. The combined period of La Nina and IOD (-) (2010 and 2016) illustrated the SSC began to increase in May to September and in October began to decline.

Interannual climate variability (ENSO and IOD) affects the distribution of SSC in Indonesian territorial waters [4][5][6]. As described on Figure 3, during 2003-2004 described an increase in SSC in the Bali Strait. This is related to the incidence of positive IOD in that year and moderate El Nino in 2002-2003 and weak El Nino 2004-2005. An increase in SSC in the Bali Strait and surrounding waters occurred in 2006-2007 associated with a weak El-Nino event that coincided with positive IOD.

![Figure 3](image-url)

**Figure 3.** (a) Climate index graph of ONI vs DMI, (b) Hovmoller diagram of SST anomaly, and (c) Hovmoller diagram of SSC anomaly in the Bali Strait.

In 2011-2012 there was an increase in SSC in the Bali Strait and surrounding waters which coincided with weak La Nina and positive IOD. The increase in SSC occurred again in 2015-2016 in the Bali Strait and the increasing of SSC in the surrounding waters began in 2014-2016. The period of 2014-2015 was
a positive IOD year and a very strong El Nino occurred in 2015-2016. Seasonal and inter-annual variability can also be seen from the SSC anomaly as the result of Aqua/Terra MODIS satellite data analysis. During the east monsoon, the SSC tends to be higher than during the west monsoon. In El Nino years and positive IOD, the anomaly distribution of SSC tends to be higher than in normal years. The weak El Nino phenomenon occurred in 2004-2005, 2006-2007; Moderate El Nino occurred in 2002-2003 and 2009-2010; El Nino was very strong in 2015-2016, while positive IOD occurred simultaneously in those El Nino years.

4. Conclusion
The upwelling process that occurs in the Bali Strait and surrounding waters can be explained by the spatial and temporal abundance of chlorophyll-a. During the eastern monsoon (JJA) and transition (SON) SSC were high, JJA (1.29 mg.m-3) and SON (1.14 mg.m-3). SST was relatively cooler in the JJA period reaching 26.52 °C and SON reaching 27.18 °C. Water conditions with low SST, and high chlorophyll-a abundance are the impacts of the coastal upwelling process identified in April-November in the Bali Strait and surrounding waters. The inter-annual climate variability (ENSO and IOD) has a significant influence on the abundance of chlorophyll-a in the Bali Strait and the surrounding waters. The ENSO period has La Nina and El Nino phases, while IOD has positive and negative phases. During the observation there were 7 patterns of occurrence, including 4 single phases (La Nina, El Nino, IOD Positive and IOD negative) and 3 combined phases. Single phase incidence years include 2000, 2007 (La Nina), 2002, 2004, 2009 (El Nino), 2003, 2012 (IOD positive), 2001 and 2013 (IOD negative). Whereas in the years of combined events, they were 2006, 2015, 2018, 2019 (El Nino and IOD positive), 2011, 2017, (La Nina and IOD positive), 2010 and 2016 (La Nina and IOD negative). During the observation, it was known that the mean range of SSC concentrations (0.49 - 1.91 mg.m-3) and SST values (25.32 - 29.30 °C). SSC anomalies during the observation period were between -0.04 - 0.62 and SST between -0.66 - 1.47. So, it is known that the period that causes an increase in high SSC and a decrease in SST in the Bali Strait was during the El Niño period along with positive IOD phases in 2006, 2015, 2018 and 2019. The ENSO phenomenon in the Bali Strait and the surrounding waters is not clearly visible compared to the DMI (Dipole Mode Index) phenomenon on the increase in SSC. The combination of the phenomenon of ENSO and IOD on the increase in SSC in the upwelling process that occurs in the Bali Strait and the surrounding waters was more dominant due to occurring during the east monsoon as a result of strong regional wind movements associated with the monsoon climate system. When ENSO and IOD phenomena occur, the abundance of chlorophyll-a will vary according to the combination of these phenomena.

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