Seasonal coastal upwelling in the Bali Strait: a model study

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Abstract. Bali Strait is part of fisheries management zone (WPP 573), where abundant fishery potential, of lemuru fish commodity. Here, physical oceanographic setting such as upwelling event plays an important role on maintaining high primary productivity and lemuru fish distribution. This study aims to describe physical process and dynamics of seasonal coastal upwelling using time-series datasets (2008 and 2014) of temperature, salinity, current velocity, surface chlorophyll-a (chl-a) from INDESO model and satellite imagery. The results showed that upwelling in the Bali Strait only during the southeast monsoon period when the south-easterly wind force surface Ekman drift of about 5.5 x 10^{-3} Sv flowing south-eastward (toward offshore). Upwelling event is characterized by minimum parameter of sea surface temperature (24.93 °C), and sea level anomaly (0.75 m), but maximum of surface chlorophyll-a (1.33 mg/m³). Furthermore, isotherm of 26 °C and Isohaline 33.7 psu are outcropped at sea surface in the center of upwelling zone. In contrast, during the northwest monsoon period these isolines remain at deeper layer of about 80-90 m depth. Mean temperature-based upwelling index during peak of upwelling in August (1.19±0.19 °C). Upwelling impact on high abundance of lemuru fish (Sardinella sp.) production two month later after peak of chl-a.

Keywords: Bali Strait, coastal upwelling, Ekman transport, INDESO model, lemuru fish, monsoonal winds, surface chl-a

1. Introduction
Bali Strait is a semi-enclosed sea with shallow bathymetric conditions with potential fishery resources (WPP-R1 573). Bali Strait is connected to the Bali Sea in the north and the Indian Ocean in the south, while the west and east sides are bordered by Java Island and Bali Island [1]. Bali Strait waters are strongly influenced by the Monsoon system. The Monsoon system in Indonesia is divided into 2, Southeast Monsoon and Northwest Monsoon. Southeast Monsoon is caused by the influence of the southeast monsoon winds that blow from Australia to Asia, while Northwest monsoon is caused by the influence of northwest monsoon winds that blow from Asia to Australia.

The maximum current velocity during Southeast Monsoon by the wind up to 0.5 m/s [2]. The wind is one of the generating factors of surface currents. High wind velocity and intensity will cause the surface water mass to move to the south. The movement of the water mass will cause a void in the surface layer. The void will be replaced by the water mass layer below it. This process is commonly known as the upwelling phenomenon.

The upwelling phenomenon significantly impacts the fertility of the waters, then increases fishery catches potential. The Bali Strait is included in an area with potential fishery resources. The research on the relationship between fishery catch potential and the upwelling phenomenon is still fascinating to study. Therefore, this study aims to describe the mechanism of the upwelling phenomenon in the southern Bali Strait in relation to the lemuru fish catches potential.
2. Methodology

The study is located in Bali Strait, with the focus of the study area at coordinates 8.6°S – 8.8°S and 114.85°E-115.05°E (Figure 1). The data period that was used in this study is 7 years from 2008 to 2014. The main data is the output data of the INDESO 3-dimensional ocean circulation model in the form of daily average data on temperature, salinity, sea surface height (SSH), mixed layer depth (MLD) and currents with a data range of 7 years period (January 2008 to December 2014). The wind data was obtained from ECMWF Reanalysis 5-th Generation (ERA5). The data on lemuru fish catches were obtained from monthly data on lemuru fish production in Coastal Fishing Port (PPP) Muncar from various types of fishing gear from 2013 to 2014. This study also used satellite imagery data using data parameters of sea surface temperature (SST), sea surface height (SSH), and chlorophyll-a. SST and SSH data from satellite observation are used for INDESO model validation. The computer software to analyze the data used in this research was Ferret, ArcGIS, and Microsoft Excel software.

![Study area map of Bali Strait.](image)

**Figure 1.** Study area map of Bali Strait.

2.1. Data analysis procedure

Processing started by validation data processing, then visualization data processing out and interpreted. The flow chart of data processing can be seen in Figure 2. Visualization of physical characteristics using INDESO main data, satellite data used for validation and supporting data on the impact of upwelling phenomenon such as abundance of phytoplankton.
2.2. Data validation with diagram Taylor method
The validation aims to know the closeness between the satellite observation and INDESO model, this study uses the Taylor diagram that contains RMSE, correlation coefficient, and standard deviation component. The parameters for validation are SST and SSH that are obtained using a sampling box with domain 8.6°S – 8.8°S and 114.85°E-115.05°E, as shown with the red box in Figure 1.

2.3. Spatial analysis, cross-section depth-longitude analysis, cross-section depth-time analysis
Spatial distribution analysis of SST, salinity, current, chl-a, and wind parameters. Analysis of the cross-sectional distribution of temperature and salinity parameters from the surface to 200 m. Depth-time plot analysis of the parameters of temperature, salinity, and vertical currents from the surface to a depth of 200 m in the period 2008 to 2004.

2.4 Estimation of Ekman's transport volume
The calculation of total transport in Bali Strait is calculated using the Ekman volume transport approach along a line, as shown in Figure 1. The transect along the yellow line parallel to the coast. The equation for calculating the total transport along the transect is presented in equation 1 [3-4].

$$Q_{Esum} = \Delta x \sum_{i=1}^{n} \frac{\tau y_i}{\rho f}$$

Description:
- $Q_{Esum}$ = Value of total transport (m³ s⁻¹)
- $\rho$ = Density of seawater (kg m⁻³)
- $\tau y$ = Longshore wind friction (kg m⁻¹s⁻²)
- $f$ = Coriolis parameter (rad s⁻¹)
- $\Delta x$ = distance A-B yellow transect line as sketched in Figure 1

2.5. Temperature upwelling index
The high upwelling phenomenon is indicated by high index value and vice versa. The temperature Upwelling Index (TUI) equation is stated [5], as follows:
4th International Conference Marine Sciences (ICMS 2021)  
IOP Conf. Series: Earth and Environmental Science 944 (2021) 012055  
doi:10.1088/1755-1315/944/1/012055

\[ TUI = \text{SST}_{\text{offshore}} - \text{SST}_{\text{inshore}} \]  

(2)

2.6. Relationship between upwelling index, chl-a and lemuru catch data
Cross-correlation analysis is used to determine the relationship and indirect effect between TUI and chlorophyll-a on lemuru fish catches. Cross-correlation analysis is also used to determine the appropriate time lag to get the highest correlation value. The cross-correlation equation is expressed [6], as follows:

\[ r_{xy} = \frac{C_{xy}(k)}{\sqrt{C_x(0)C_y(0)}} \]  

(3)

Description :
- \( r_{xy} \) = Cross correlation function
- \( C_{xy}(k) \) = Cross covariance function
- \( C_x(0) \) = Data series standard deviation function \( x \)
- \( C_y(0) \) = The standard deviation function of the data series \( y \)

3. Result and discussion

3.1. Data Validation
The validation result contains 3 components: standard deviation, RMSE, and correlation coefficient. From the Taylor diagram between the SST parameter from the INDESO model and the satellite observation (Figure 3), the standard deviation value is 1.62, RMSE is 0.5, and the correlation coefficient is 0.96. RMSE value that is closer to 0 indicates the value has higher accuracy (RMSE ≤ 1) [7]. The high correlation between the two data is close to 1 or -1 [8]. These results show that the output of the INDESO model can be representative of the actual value.

![Figure 3. Taylor diagram and graph of INDESO – SST satellite data from 2008 – 2014 taken in the sampling box of the Bali Strait study area.]

3.2. Variation of oceanographic parameters at the peak of different seasons
Oceanographic parameters (e.g., surface currents, SST, salinity, and chlorophyll-a) experience different variations every time, especially during the Northwest and Southeast monsoons (Figure 4). During the west monsoon, it is characterized by weak surface currents (0.1 m/s to 0.35 m/s), SST values are also relatively high between 29.69 °C to 29.81 °C, while the values of salinity and chl-a tend to be low. The salinity ranges from 32.46 psu to 32.89 psu, and chlorophyll-a ranges from 0.2 to 0.5 mg/m³. The southeast monsoon has significantly different characteristics, inversely proportional to the West monsoon with faster current velocity ranges from 0.2 m/s to 0.5 m/s. SST values also tend to be low between 25.06 °C to 26.44 °C. In contrast, the value of salinity and chlorophyll-a tend to be high. Salinity ranges from 33.64 psu to 33.83 psu, and chlorophyll-a ranges from 0.8 to 3 mg/m³. South Equatorial Current (SEC) flows towards the west, which occurs throughout the year and strengthens in the Southeast Season [9]. Indication of upwelling in certain seasons is followed by an increase in water productivity which is detected with low SST and high chlorophyll-a [10-11]. Areas that experience an upwelling process always have a higher salinity value than the surrounding area [12].
Vertically, the temperature and salinity values also fluctuate every season. This can be seen from the thickness of the MLD layer and the location of the isotherm/isohaline in the Southeast and Northwest monsoons (Figure 5). The Northwest Monsoon has a thicker MLD layer than the Southeast Monsoon. The isotherm value of 26 °C and isohaline 33.7 psu at a depth of 90 m in the Northwest monsoon was also raised far to the surface. This characteristic is a phenomenon of upwelling. Central upwelling is seen at coordinates 115 °BT and 8.7 °LS because there are several isotherms and isohalines reaching the surface.

The depth-time plot also shows that temperature, salinity, and vertical current velocity fluctuate over time. There is a significant difference pattern between the Southeast Monsoon and the Northwest Monsoon (Figure 6). Northwest Monsoon has isotherm and isohaline characteristics that sink into the water column, and the value of vertical current velocity is negative. In contrast to the Southeast Monsoon, whose characteristics show the isotherm and isohaline values lifting to the surface, the current velocity value is positive. The vertical current that moves up from a certain depth to the upper layer/surface, wherein the simulation results image is represented by the Velocity $w$ parameter which is positive, which is an indication of upwelling [13].
3.3. Estimation of Ekman’s transport volume

The wind is the main factor in generating Ekman transport of water mass. In the Southern Hemisphere, the current is deflected to the left. On Northwest monsoon, the direction of Ekman’s transport is towards the coast, which is represented by a positive value and vice versa. On Southeast Monsoon, the direction of Ekman’s transport is away from the coast, which is represented by a negative value (Figure 7). The accumulation of water masses towards the coast causes the water level to tend to rise. Therefore, the water mass will press the bottom and move down (downwelling) to achieve balance. At the same time, the effect of mass transport of water away from the coast will cause a void of water mass which will then be filled by the mass of water below it (upwelling) [10]. Climatologically, the upwelling phenomenon begins in April and ends in November. The peak of upwelling occurs in July and August (Figure 8).

Figure 6. Depth-time plot of seawater temperature, salinity and vertical currents in the Bali Strait between the surface to 200 meters.

Figure 7. The direction of the climatological wind speed in the Northwest and Southeast monsoon.
3.4. Relationship between upwelling index, chl-a and Lemuru catch data

Based on Temperature Upwelling Index (Figure 9), the cooler temperature at the nearshore is represented by a positive value. TUI values tend to be negative, which indicates a downwelling phenomenon at that time [14]. The upwelling phenomenon directly affects the fertility of the waters, while has two months time-lag on lemuru fish catches after the peak of chl-a (Figure 10). An indirect relationship appears between chl-a, and lemuru fish catches due to the time-lag use of chl-a as food for zooplankton [15].

4. Conclusion

The upwelling center appears on the east side of Bali Strait. The upwelling phenomenon in the Bali Strait is characterized by low sea surface temperature, high salinity, low sea level, and high chlorophyll-a. The upwelling period occurs from April to November, with its peaks in July and August. Upwelling has implications for water productivity (chl-a) and affects lemuru catches with two months time-lag after the peak of chl-a.

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