Seasonal Ekman upwelling in the Southwest Sumba from INDESO Model

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Abstract. Southwest Sumba water is part of the Indonesian fisheries management region (WPP573). Marine fisheries resources are influenced by oceanographic phenomena such as an upwelling event. This study aims to describe characteristics of seasonal Ekman upwelling by analyzing oceanographic parameters from the validated INDESO model output (2008-2014). It shows that upwelling event in the study area occurs during the Southeast Monsoon period, which creates an Ekman drift of 0.26 Sv towards offshore. This transported water mass is then replaced by an upwelled vertical flow of sub-surface colder and nutrient-rich water at the velocity of the order of $10^{-4}$ m/s. Surface features of the upwelling event are seen from a minimum temperature (24.3 °C), sea level anomaly (0.34 m), but the maximum of chlorophyll-a (3.02 mg/m$^3$). During this time, an uplifted isotherm of 25.5 °C is found from sub-surface to 10 m depth, but it is outcropped at the sea surface in the centre of upwelling area. Interestingly, during upwelling event, salinity stratification revealed an isohaline of 34.10 psu is much deeper at 40 m depth, and much fresher water mass from the Ombai Indonesian Throughflow water is dominant. Averaged temperature-based upwelling index between June-September is about 0.3 °C.

Keywords: Ekman, INDESO, Indonesian Throughflow, monsoon, Sumba, upwelling

1. Introduction

Sumba Island, with an area of about 10710 km$^2$, is located in the southern part of the small Sunda arcs, which is directly connected with the Savu Sea on the east side and the Indian Ocean on the west/south side, while in the north and southeast by the Sumba Strait and the Ndao Strait (Figure 1). The Savu Sea is one of the main outflow straits of the Indonesian Throughflow (ITF), which exits through the Ombai Strait. The transport volume of the ITF through Ombai is around 4.9 Sv – which is the second largest after the Timor passage (7.6 Sv) and brings ITF water masses from Flores and Banda [1, 2]. The ITF pathway from Savu exits to the Indian Ocean via the Ndao Strait and the Rote Strait in southeastern Sumba. So that ITF passing this strait is considered to impact the dynamics of local circulation and marine fishery resources around Sumba [3]. As part of the Indonesian fisheries management area (WPP-573), Sumba waters are known as one of high marine fisheries resources, particularly for large pelagic fisheries [4].

The seasonal reversal Asian-Australian monsoon winds system controls significantly the general climate characteristics in Indonesia, as well as in Sumba [5]. During the Southeast Monsoon period (May – October), dry and cold air mass from Australia carried by the monsoon winds causes dry and cold climatic conditions here. However, strong and persistent fully developed Southeast Monsoon winds
create a coastal upwelling event in the southwest part of Sumba, which can be characterized by a minimum sea surface temperature and a maximum surface chlorophyll-a [6].

Previous upwelling studies in the Sumba waters have revealed the sea surface features of the upwelling event and the period of upwelling event [7]. However, there are still remaining questions that are not understood well, such as how is the mechanism of the Ekman upwelling event here? How are the changes of vertical stratification of temperature and salinity during upwelling events? Moreover, what is the impact of ITF passing the Ndao Strait on the intensity of upwelling events in southwest Sumba?

This study aims to analyze the physical processes and dynamics of coastal upwelling, including upwelling mechanisms and dynamics, vertical stratification analysis of water masses, and upwelling transport volume estimation in southwest Sumba waters, using multi-datasets from the validated INDESO ocean circulation model output and satellite imagery data. The results of this study are expected to provide useful marine information associated with coastal upwelling in Sumba, which stakeholders can utilize in making fisheries policy decisions in WPP-573 and marine conservation policy.

2. Materials and Methods

2.1. Study Area

The study area is located in the Sumba waters with particular analysis in the southwest Sumba (Figure 1, red rectangle).

Figure 1. Study Area of Southwest Sumba. In the upwelling area, red rectangle denotes for sampling box of parameters of the dataset time-series. The yellow line represents a transect for Ekman drift calculation from cross-shelf winds velocity. Blue dashed-line is a transect for analysis of vertical stratification of water properties (temperature and salinity). Three small white rectangles are for vertical (upwelled) velocity calculation. The daily averaged multi-datasets time-series used in this study are daily from January 2008 to December 2014 (7 years).

2.2. The multi-datasets

The time-series datasets used in this study are obtained from the ocean model output and satellite-derived ocean parameters (sea surface height—temperature—chlorophyll-a). The ocean general circulation model simulation performed by the CLS centre in Toulouse as part of the INDESO
(Infrastructure Development for Space Oceanography) project of the Indonesian Ministry of Marine Affair and Fisheries. The INDESO model output datasets consist of daily average temperature, salinity, sea level, and zonal & meridional current components covered from 1 January 2008 to 31 December 2014 (7 years). The satellite imagery datasets are Sea Surface Height (SSH), Sea Surface Temperature (SST), and Chlorophyll-a. SSH derived from multi-mission Data Unification and Altimeter Combination System (DUACS) datasets. The datasets are derived from the observation data of satellites altimetry Jason-3, Sentinel-3A, HY-2A, AltiKa, Cryosat-2, Jason-2, Jason-1, T-P, ENVISAT, GFO, and ERS1/2 with spatial resolution of 0.25°. The SST datasets are obtained from Aqua MODIS level-3 satellite with a resolution of 4 km. The Chl-a datasets are obtained from monthly LEVEL 1 MODIS satellite with the spatial resolution of 4 km and daytime data acquisition and can be downloaded from the website at https://oceancolor.gsfc.nasa.gov. Wind data are downloaded in zonal (u) and meridional (v) wind components at 10 meters above sea level. Data can be downloaded on the page http://cds.climate.copernicus.eu. Data are downloaded in NetCDF file format.

2.3. Data Analysis
Ekman upwelling area is analyzed by delineation of temperature contours that identify as an upwelling area using ArcGIS tools, while time-series datasets are analyzed with Pyferret and Matlab.

![Figure 2](image-url)  
**Figure 2.** The current scheme rotation, calculation of Ekman transport along the A-B line, and Ekman vertical speed in the upwelling area southwest of Sumba. Conditions in the August period are used in this sketch. Grids 1-3 are created to calculate the vertical speed represent onshore, transitions, and offshore.

The coastline orientation of the study area in southwest Sumba is northwest-southeast direction. Since the coastline is not aligned east-west direction, thus the wind and current components datasets need to be rotated to obtain cross-shore velocity (CSV) and along-shore velocity (ASV) components [8]. In this study rotated angle is about 43° to the north. Rotation is performed against an angle value

\[
\begin{align*}
CSV &= u \cos \theta + v \sin \theta \\
ASV &= -u \sin \theta + v \cos \theta
\end{align*}
\]  

(1)
that takes a value of 0° towards the north (Figure 2). Rotated current components is calculated using Equation (1) [9].

The total transport in the Southern region of Sumba is calculated using Ekman volume transport approach along a line as presented in Figure 2. The transect line is called line A-B. The equation for calculating the total transport along the transect line A-B is presented in Equation (2) [10] where \( Q_{\text{Total}} \) is the value of total transport (m³/s); \( \rho \) is density of seawater (kgm⁻³); \( \tau_y \) is alongshore wind drag; \( f \) is Coriolis parameter; \( \Delta x \) is distance of A-B as sketched in Figure 2.

\[
Q_{\text{Total}} = \int_0^L Q_{\text{ed}} dx = \Delta x \sum_{i=1}^n Q_{Ei} = \Delta x \sum_{i=1}^n \frac{\tau_y}{\rho f}
\]

(2)

The results of the calculation of Ekman transport volume total for 7 years (2008-2014) are displayed in the form of bar graphs with monthly averages. Assume that Ekman transport value is negative, then it indicates the occurrence of upwelling process otherwise if the value is positive indicates downwelling process [11]. Vertical speed values were also calculated in this study. The vertical speed of the Ekman layer is associated with convergence and divergence of water mass. Vertical speed values indicate the convergence of Ekman transport on the surface that moves the mass of water towards the coast. If the vertical speed has a positive value, it indicates the occurrence of divergence on the surface that moves the mass of water towards the sea associated with upwelling process. Ekman’s vertical speed is calculated using [12]:

\[
-\rho \frac{\partial \text{we}}{\partial y} = \text{curl}[\tau_y f] = \frac{\partial}{\partial x} \left( \frac{\tau_y}{f} \right) - \frac{\partial}{\partial y} \left( \frac{-\tau_y}{f} \right) = \frac{\partial M_{xe}}{\partial x} - \frac{\partial M_{xe}}{\partial y}
\]

(3)

Three rectangles grid of 0.25° × 0.25° are used to calculate the vertical velocity component, as shown in the small white boxes (Figure 2). This is based on the number of wind data points where one new grid represents one vertical speed value in the region. Each grid represents the coastal area, the transitions area, and offshore area.

The temperature-based upwelling index (TUI) is calculated from the difference between offshore sea surface temperatures and onshore area. Grid 1 and grid 3 is selected to represent the onshore and the offshore area, respectively (Figure 2). Much higher index value indicates much stronger upwelling intensity. The upwelling index equation by temperature is expressed, as [13]:

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

(4)

Validation of the model is done by comparing datasets between INDESO model output and satellite imagery data. Sea surface temperature and sea level data from satellite imagery likened the coordinates. The validation calculation is done by specifying the value root mean square error (RMSE), which is a measure that can be used to determine the level of accuracy between the data values of the model results and the values of observation satellite data calculated through:

\[
\text{RMSE} = \sqrt{\frac{\sum_{i=1}^N (X_{\text{model}}(i) - X_{\text{observation}}(i))^2}{N}}
\]

(5)

where \( X_{\text{model}} \) is model data results to \( i, i=1 \ldots N \); \( X_{\text{observation}} \) is observation satellite data to \( i, i=1 \ldots N \); \( N \) is number of data

Validation between model and satellite data were done by using correlation coefficient formula. Correlation coefficient \( r \) is a way to determining how well the relationship between two or more

\[
r = \frac{1}{N-1} \sum_{i=1}^N \left( \frac{(x_i - \bar{x})(y_i - \bar{y})}{S_x S_y} \right)
\]

(6)
variables [9]. If \( r \) value is close to 1, it means the accuracy value between the model data and the satellite data is good. Correlation coefficient values are defined using:

\[
\text{where, } r \text{ is correlation coefficient (between -1 and +1); } N \text{ is number of data; } x_i, y_i \text{ is the } i^{th} x \text{ and } y \text{ data; } \]

\[x, y \text{ is average of } x \text{ and } y; S_x, S_y \text{ is standard deviation of } x \text{ and } y \text{ data.}\]

Figure 3a shows the sea surface temperature of the satellite (red) and the data of the INDESO model (black) in Southwest Sumba. Differences in satellite data and INDESO models occur due to different resolution levels. The RMSE value at temperature validation is 0.4. The correlation coefficient between satellite observations and model is 0.9704. Figure 3b shows the comparison of model and satellite observation SSH. RMSE SSH observation and model is 0.04. The result of the correlation coefficient of SSH obtained is 0.87. The low RMSE value indicates that the model data is close to the actual value [9]. The correlation coefficient shows the level of accuracy between the INDESO model and satellite data is very high. Thus, INDESO model is suitable for further analysis. So, it can be said that the INDESO model used is sufficiently representative that are closed to reality in the study area.

3. Results and Discussion

3.1. Contrast of Seasonal Oceanographic Variations
The southwest Sumba waters is an interesting study area because it revealed a strong seasonal variation of parameters that is clearly visible from the distribution of SST, SSH, and chl-a. Figure 4 shows the spatial distribution of monthly averaged (2008-2014) sea surface temperatures in January and August, a representation of peak seasons. SST distribution in August shows distribution with lower temperature values. SST distribution in August is in the range from 24.3–28.4 °C. The Lowest SST area can be seen around the southwest side of Sumba and south of Flores. An intensive upwelling area is characterized by a minimum SST in the region. The centre of upwelling area appears in Southwest Sumba. SST gradually decreases towards the southwest area. The Southeast Monsoon winds are factors that play a role in changing surface temperature distribution. During the Southeast Monsoon period, the monsoon winds cause surface currents flow southwestward due to the influence of Coriolis that deflecting surface currents from wind direction to the left in the southern hemisphere [14]. So, the low SST will distribute towards the southwest. Upwelling area in Southwest Sumba with isotherm of 25.8 °C reached 11,536
km². The isotherm was chosen because according to [6] stated that the sea surface temperature in the upwelling region < 26 °C.

Another location that becomes the centre of upwelling is south of Flores. This location has a smaller upwelling area compared to southwest Sumba and has a different distribution direction. Upwelling evolution from east to west. This mechanism is due to the pattern of wind blowing to the west and northwest along-shore in the coast of Flores.

Chlorophyll-a distribution in January is lower than that in August (Figure 5). The distribution of chlorophyll-a in January ranges from 0.01 – 1.2 mg/m³. The low chlorophyll-a distribution in January appears in the Indian Ocean region, but there is a location that indicates high chlorophyll-a north of Flores. The low concentration of chlorophyll-a in January is due to no upwelling, so chlorophyll-a is relatively lower compared with August. There was no uplift chlorophyll-a from a bottom layer in this month. Chlorophyll-a in August ranges from 0.3 – 3.1 mg/m³. High chlorophyll-a distribution was detected in Southwest Sumba and South Sumbawa as well as south of Flores. Upwelling area in southwest Sumba with a standard of 0.62 mg/m³ reaches 9,127 km² with a distribution pattern is similar to cooling SST area. The high number of chlorophyll-a in August related to upwelling phenomenon. The increase in chlorophyll-a is due to the intensively upwelling mechanism [6].

Figure 4. Seasonal variation of monthly averaged sea surface temperature in January (a) and August (b) in the Southwest Sumba and surrounding areas.

Figure 5. Seasonal variation of monthly averaged surface chlorophyll-a in January(a) and August(b) in the Southwest Sumba and surrounding areas.
The distribution of SSH is shown in Figure 6. It appears that January tends to have a higher SSH value than in August. SSH distribution in January ranges from 0.57–0.72 m. High SSH distribution was detected in the Indian Ocean region. SSH distribution in August has lower value which ranges from 0.37–0.65 m. The lowest SSH appears in Southwest Sumba, which distributed southwestward and then westwards. There are also other areas with a minimum value of SSH such as Savu Sea. The decrease of sea level could be influenced by the presence of upwelling phenomenon in the region [15]. This confirms that the intensifying decrease of SSH in August is influenced by upwelling due to the transport of water mass in the surface layer in the Southeast Monsoon wind [8]. Upwelling area in Southwest Sumba with a standard of 0.36 m reached 6188 km$^2$. Decrease SSH also occurred in Savu Sea.

![Figure 6. Seasonal variation of monthly averaged sea surface height in January(a) and August(b) in the Southwest Sumba and surrounding areas.](image_url)

Seasonal variation of vertical stratification of temperature is evidenced. Cross-section distribution of temperature indicates the distribution of water mass in the water column during January and August (Figure 7). The cross-section is integrated with the blue tick-dot line in Figure 1. The temperature difference in January and August was about 4 °C at 20 m depth which was much colder in August. The deeper layers isotherm variations are more homogeneous between January and August. It has a difference about 1 °C at 280 m depth. Major upwelling was found at coordinates 120 °E, indicated by deepening isotherms of 25.5 °C and it outcropped to the sea surface. This result corresponding with spatial distribution of SST, which is lower during August.

The cross-section of salinity shows that there were tight contours in the upper 20 m depth in January and a depth of 40 m to 140 m in August (Figure 8). There are different fluctuations in the deeper layer and surface layers between January and August. In January, it was seen that the salinity value in the deeper layer tends to be lower compared to the deeper layer in August. The pattern of fluctuations in the surface layer reveals something different. Central upwelling at coordinates 120 °E in January is found isohaline of 34.10 psu at a depth of 20 m and 34.07 psu at a depth of 5 m. In August, isohaline of 34.10 psu actually decreased to a depth of 30 m, but isohaline 34.07 psu was outcropped to the surface. This proves that in the central area of upwelling there is an uplifting of the water mass, which is an indicator of upwelling with small intensity where isohaline uplift reached 5 m depth only. On the contrary, isotherm 25.5 °C uplift reached 60 m depth. Different from the surrounding area, the area that did not become the central upwelling in August actually has a lower salinity and contrast than January in the surface layer. This does not correspond with the upwelling theory that states the salinity value on the surface at the time of upwelling is higher.
Figure 7. Depth-longitude section (blue dashed transect in Figure 1) of monthly averaged temperature in January (a) and August (b).

Figure 8. Depth-longitude section (blue dashed transect in Figure 1) of monthly averaged salinity in January (a) and August (b).
To test this, need to be done visualization of monthly averaged distribution salinity in August and January with a current vector at 50 m depth shown in Figure 9. That depth was chosen because isohaline in January and August has a large difference in the upper of 50 m depth. The results show that salinity value in August had a lower value, which associated with strong current entering the study area. This current is part of the Ombai ITF through the Savu Sea and Ndao Strait. This is in good agreement with a previous study [2] which states that low salinity in the upwelling period occurs due to the contribution of ITF which carries water with a lower salinity sourced from the Java Sea. Low salinity in the Java Sea is influenced by high rainfall and runoff of several major rivers, then in 5-6 months the mass water enters the southwestern area of Sumba.

Figure 9. Monthly mean of model current vectors in 50 m depth and its temperature in January (a) and August (b).

Figure 10 shows the depth-time distribution of seawater temperatures. Figure 10 gives an overview between 0-500 m depth. The fluctuations can be known as the presence of seasonal temperature changes. In the Northwest Monsoon period, it is clearly seen that water temperature is generally higher than in the Southeast Monsoon period. The fluctuation of isotherm 25 °C indicates the presence of upwelling in the Southeast Monsoon to 40 m depth and several times outcropped to the surface in 2008 and 2012. The isotherm of 25.5 °C in the Northwest Monsoon decreased to 100 m depth which peaked in January. Isotherm 25 °C can uplift until 75 m in the Southeast Monsoon period. Results showed strong isotherm fluctuations up to a depth of 200 m in the upwelling period.

Figure 10. Depth-time section (red rectangle in Figure 1) of seawater temperature between 0-500 m from 2008-2014.
Figure 11 shows salinity values at depths of 0-500m from 2008-2014. Salinity fluctuations are clearly seen for example isohaline 34.3 psu in the Southeast Monsoon at a depth of 100 m while in the Northwest Monsoon isohaline can uplift to a depth of 80 m and some were outcropped to the surface in 2009, 2010, and 2013. Upwelling period in the Northwest Monsoon tends to have lower salinity and minimum in 2014, where the upwelling period of the year had a value of 34.06 psu. The depth of 100 m to the surface in the Southeast Monsoon tends to be dominated by freshwater. This occurred due to the influence of ITF inputs that entered through the Makassar Strait which then moved through southwest Sumba which became the location of this study.

The Depth-longitude section of zonal current are presented in Figure 12. In January, the vertical profile of the current speed of zonal components showed a dominant flow of water mass to the west, but there was also a point stating eastwards at a depth of 20 – 60 m. The vertical distribution of zonal currents in August is stronger than in January with the speed of zonal currents on the surface layer strong towards the west, then weakening to close to 0 m/s at a depth of 220 m. The vertical profile of the current speed component in the zonal (east-west) direction shows a strong flow of water mass towards the west in a depth layer of 10-60 m to 0.6 m/s. The movement of currents on the right side of the central region upwelling both in January and August looks very strong. This is due to the influence of ITF intensity which is very intensive towards the region.

Figure 11. Depth-time section (red rectangle in Figure 1) of seawater salinity between 0-500m from 2008-2014.

Figure 12. Depth-longitude (blue dashed transect in Figure 1) of monthly averaged zonal current between 0-300m in January (a) and August (b). Positive scale indicates eastward and negative indicates westward. A vertical red dashed line in the longitude of 120°E denotes the central region of upwelling.
The meridional current component shown in Figure 1. In August, the speed of meridional currents on the surface layer is stronger than in January which is both move towards south. In January, meridional current component revealed southward flows above 0.2 m/s, although there was also a point revealed northward flow below 60 m depth with a weak intensity of about 0.04 m/s. The meridional current component in August showed strong southward flow at a depth of 10-60 m with a maximum speed of 0.4 m/s, although there is also a point that moves towards north below 20 m depth with a weak flow of about 0.04 m/s. The movement of currents on the right side of the central region upwelling both in January and August looks very strong. This is due to the influence of ITF intensity which is very intensive towards the region.

Figure 13. Depth-longitude (blue dashed transect in Figure 1) of monthly averaged meridional current between 0-300m in January (a) and August (b). Positive value indicates the direction to the north and negative indicates the direction to the south. A vertical red dashed line in the longitude of 120°E denotes the central region of upwelling.

Figure 14. Depth-longitude (black dashed transect in Figure 1) of monthly averaged rotated zonal current between 0-300m in January (a) and August (b). The positive scale shows the direction towards inshore and the negative indicates the direction towards offshore.
Rotated zonal distribution is also done to determine seasonal variations of currents that move towards offshore. The rotated zonal component in the direction of 43° is shown in Figure 14. Rotated zonal current visualizations are integrated diagonally into 40 points. The first point is near the coast, so the negative value indicates the movement of the current perpendicular to the Sumba coastline and the positive value indicates the movement of the current towards coast. In January, a rotated of the current speed in zonal component showed that the dominant water mass distributes towards offshore, but there was also a point that moved towards coast at a depth of 20-60 m. In August, the rotational zonal current speed is homogeneous in surface layer towards offshore with maximum speed of 0.6 m/s, then weakening to close to 0 m/s at a depth of 220 m. Cross shore velocity towards onshore in the lower 220m depth during August.

3.2. Ekman Upwelling Dynamics

Ekman dynamics in the surface layer were composed of Ekman transport in the surface and Ekman vertical speed, which could be associated with the occurrence of upwelling phenomenon. The total transport average is calculated by integrating the length of the area upwelling region, which has SST with 25.6 °C isotherm in August from 2008-2014 (Figure 2). Total transport with monthly average is presented in Figure 15.

In general, the total transport is positive in the Northwest monsoon. This indicates that the mass water direction is transported towards coastline southwest of Sumba. The peak transport in the Northwest Monsoon period occurred in January with the total transport approaching the onshore of 0.25 Sv (1 Sv = 10^6 m^3/s). Transport decreased after the January period. The decrease in transport occurred until March. Wind conditions in April were weakened and changed toward offshore. April is the first phase of transport leaving the coastline. This can be seen from the change in the value of transport in April which changed to negative. The total transport towards offshore in April was 0.10 Sv.

The total transport volume in the Southeast Monsoon shows a pattern of increasing the total volume of transport from the beginning of the Southeast Monsoon period in May and maximum in June. The total volume of transports toward offshore during June was 0.26 Sv. The total volume transport showed an increase in transport volume from the early period of the Southeast Monsoon to the peak period in the Southeast Monsoon. The increase of upwelling intensity will be associated with an increase of transport volume move towards offshore [12]. The wind direction from the southeast in the Southeast Monsoon influenced Ekman transport to distribute towards the southwest (away from the southwest coast of Sumba) due to the Coriolis effect. The vacant surface water column is then replaced by upwelled water which is colder from the deeper layer [14].
Vertical speed at the observation area was calculated with the new grid area, as described in the method. Vertical speed show in the graph below (Figure 16). The difference was clearly seen between the vertical speed in Northwest Monsoon and in Southeast Monsoon. The Northwest Monsoon generally shown a positive value. This indicates the sinking of water masses associated with downwelling. In January, there is a downwelling phenomenon seen from the increase in the speed of vertical speed of the water reached 2.07 \times 10^{-6} m/s and then increased in the transition area reached 3.76 \times 10^{-6} m/s and maximum in the coast reached 15.95 \times 10^{-6} m/s. There was a similar pattern in February and December. In the Northwest Monsoon, it was concluded that the movement of the dominant water influenced the sinking of the water. In March, there was a drastic decrease in the speed of water mass sinking in areas far from the coastline reached 0.4 \times 10^{-6} m/s while in areas near the coast reached 0.98 \times 10^{-6} m/s and in transition areas actually experienced the uplifting of the water reached 0.08 \times 10^{-6} m/s. In the following month, the entire dominant region influenced uplifting water mass associated with the phenomenon of upwelling. The increase of uplifted water mass speed continued until its peak in June and gradually decreased until entering November. Grid 1 is an area that represents the area of the upwelling phenomenon with the highest intensity during June, which show the value of vertical speed reached 23.15 \times 10^{-6} m/s.

3.3. Temperature-based Upwelling Index (TUI)

The upwelling index by temperature is defined by the difference between sea surface temperature at offshore area (Grid 3) and at onshore area (Grid 1) in Figure 2. This method was adopted from [13]. The temperature-based upwelling index in the Southwest Sumba is presented in Figure 17. Black plot is time series of temperature-based upwelling, and the red plot is smoothed time series with 31-day averaged of temperature-based upwelling. It shows that TUI for 2008-2014 ranges from -1.7-2 °C. TUI during the Southeast Monsoon period is generally higher than during the Northwest Monsoon period. Negative TUI means that temperature on grid 1 (onshore) is much warmer than SST in grid 3 (offshore), and reversed. Climatologically, upwelling began in the early period of the Southeast Monsoon, then maximum in September reached 2 °C.

Upwelling intensity decreased in the period October to November and disappeared in November. In the December-March period, TUI values tend to be negative, which indicates the phenomenon of downwelling at that time [16]. The results of the upwelling index calculation consist of monthly variations of oceanographic parameters, which are maximum in the Southeast Monsoon. June to October is the peak of the upwelling phenomenon, which is also characterized by an increase in chlorophyll
concentration as well as a decrease in SST and SSH in the western region of Sumba, with central upwelling located in the area close to the coast.

4. Conclusions
The existence of seasonal Ekman upwelling in the Southwest Sumba waters is characterized by minimum sea surface temperature and maximum surface chlorophyll-a. The isotherm of 25.5 °C in the Southeast Monsoon at 10 m depth in the central region of upwelling, while in the Northwest Monsoon deepens to 80 m depth. Isohaline of 34.10 psu in the Northwest Monsoon at 20 m depth and in the Southeast Monsoon at 40 m depth. The low salinity value of 34.07 psu was revealed on the surface in the Southeast Monsoon due to the role of ITF, which brought fresh water through the study area. In addition, the presence of ITF also causes strong currents in southwest Sumba, thus increasing the intensity of upwelling in the Southeast Monsoon. Ekman transport size upwelling period of 0.26 Sv with a vertical speed of $23.15 \times 10^{-6}$ m/s. The upwelling index values the maximum sea surface temperature in the Southeast Monsoon at 2 °C. The high value of the upwelling index in the Southeast monsoon indicates the presence of a strong upwelling event in the southwest Sumba waters.

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Figure 17. Time-series of smoothed temperature-based upwelling (a) and climatology (b)
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