The classification of upwelling indicators base on sea surface temperature, chlorophyll-a and upwelling index, the case study in Southern Java to Timor Waters

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Abstract. The Understanding of the existence of upwelling, which concerning location, onset and ending, top temporally, strength, extent area are very important for the management of marine waters, especially fishing and conservation. A method is needed to identify the area of upwelling base on its indicators. The one method that is needed is to classify the upwelling indicator. The aim of the research is first studying the method classification of upwelling criteria base on SST, chlorophyll-a and upwelling index. Second, apply classification of upwelling criteria for mapping upwelling area on four case climate variability and third examine the effect of ENSO and IOD on the variability of the upwelling area. The research result, based on SST, chlorophyll-a and upwelling index in the Indian Ocean south of Java to Timor with statistical methods, have successfully divided upwelling criteria into 4: weak upwelling, medium upwelling, strong upwelling and very strong upwelling. Based on the upwelling criteria, we can apply mapping the location of upwelling, to determine the spatial distribution and extent of upwelling in Indian Ocean waters southern of Java to Timor. Two indicators of upwelling SST and chlorophyll-a are more accurate in the application if be used together. The variability of ENSO and IOD significantly effected growing and reducing the range of upwelling indicator (SST, chlorophyll-a and upwelling index), but the IOD index much greater effecting than ENSO index (SOI).

1. Introduction

The upwelling phenomenon is important to understand because it bearing with conservation as well as oceanic resource exploration. The several important aspects of upwelling concerning its location, onset and ending, top temporally, its strength, and extend area. The Upwelling evaluated from ecology facet represents the environmental fertilization process naturally. With the upwelling process, the infertile marine environment becomes fertile because the process will increase nutrient levels that are useful for the growth of phytoplankton as a major producer in the sea [1].

In the field of marine environment conservation, understanding upwelling in order to protect the area from the threat of sources of pollutants both from industry and from ship waste. Because the upwelling area is generally a place for spawning and breeding grounds for various types of fish [2]. [3].

The oceanic exploration resources field comprehend upwelling in order to assist to determine fishing ground (fishing area). The upwelling area generally has higher level fishery productivity than the other area [1], [4], [5]. The well understanding of the upwelling area is able to assist in the determination of area having high fishery productivity. Some result of research prove upwelling area...
have high fishery productivity [6]. They found that area where happened upwelling process with the character of lower sea surface temperature than surroundings and higher-level chlorophyll-a concentration in the reality have CPUE (Catch Per Unit Effort) fisheries better. [7], have proved the existence of a significant correlation between the upwelling event with the rise of Sardinella and squid fishing. [1], reveals fishery productivity in higher at upwelling area than non-upwelling area. The statement strengthened by the statement of [8], that showed catch per unit effort (CPUE/ Catch Per Unit Effort) of tuna in the southern of Java and the western of Aceh, in generally growing up as long as the occurrence of upwelling.

Based on the above description clearly understand the existence, timing and strength of upwelling is an important issue. Understanding of the presence or absence of upwelling can be done by measuring the temperature of seawater vertically with tools such as mooring or argofload. Using this tool is quite expensive, is locally and the data can not be accessed in real-time or near real-time but through longer processing. The understanding of upwelling the most rapid and inexpensive and is also commonly practiced is by looking at indicators of upwelling. Upwelling indicators including sea surface temperature and chlorophyll-a [9]; [10]; [11]; [12]; [13]. The all references above to explain the upwelling can be known by the sea surface temperature (SST) which is lower than its surroundings, and chlorophyll-a is higher than the surrounding area, but not in detail describe upwelling criteria in Indian Ocean Waters South Java to Timor base on the SST and chlorophyll-a. How large is the range of SST and chlorophyll-a monthly that occurs during upwelling periods and is there a link between the increased upwelling intensity with changes in the range of SST and chlorophyll-a? This is a research problem that needs to be studied in more detail.

This research studied comprises the method for making upwelling criteria base on sea surface temperature (SST), chlorophyll-a and upwelling index, the application that criteria for determining the upwelling in the Indian Ocean Waters south of Java to Timor in four cases of climate variability. The location research in Indian Ocean southern Java to Timor (Figure 1).

![Figure 1. The research location at Indian Ocean Southern Java to Timor Island.](image)

2. Methodology

The methodology used in this research is descriptive and statistic methods. The descriptive method is done by describing the range of values SST, chlorophyll-a and upwelling index found in upwelling regions in the Southeast of Java to Timor in the variation of ENSO and IOD events. Statistical analysis performed by calculating the average range, maximum, minimum and deviation standard of SST, chlorophyll-a and upwelling index. Base on these data is used to count criterion of upwelling
strength, and with this criterion be applied to mapping area of upwelling in four case climate variability El Nino-IOD (+), El Nino-IOD(-), La Nina IOD (+) and La Nina-IOD(-).

The research problem-solving methodology described above is divided into several stages.

1. **Primary and secondary data collection**
   The collection of primary and secondary data obtained from several internet sites, agencies, and field surveys that includes:

   1. **Monsoon data of wind speed and direction** are spatially obtained from the Internet at:  
      [http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.surface.html](http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.surface.html).  
      Data downloaded in the form of FNL (final analysis). This data is then processed by Matlab software.

   2. **Data of temperature and chlorophyll-a sea surface** derived from MODIS images, downloaded from [http://www.oceancolor.gsfc.nasa.gov](http://www.oceancolor.gsfc.nasa.gov), in the form of HDF (Hierarchical Data Format). This data is processed with the SeaDAS software. The MODIS data used Level-3, with spatial resolution 4.69 km. Data used for SST began in July 2002-December 2011, while chlorophyll-a data began in July 1997-December 2011.

   3. The SST data are also supplemented with the reanalysis results, be downloaded from [www.metoffice.gov.uk/hadobs/hadisst/data/download.html](http://www.metoffice.gov.uk/hadobs/hadisst/data/download.html), the period 1987-2011. Data resolution 1°x 1°. Data is processed with grads software.

   4. **Climate variability data** that contain ENSO index which is SST anomaly at NINO3.4 and IOD index which is DMI were collected from:  
      [http://www.bom.gov.au/climate/current/soihtml.shtml](http://www.bom.gov.au/climate/current/soihtml.shtml);  
      [http://www.jamstec.go.jp/frcgs/research/d1/iod/DATA/dmi_HadISST.txt](http://www.jamstec.go.jp/frcgs/research/d1/iod/DATA/dmi_HadISST.txt).

2. **Data Processing temperature and chlorophyll-a image of MODIS and**
   Data chlorophyll-a and sea surface temperature MODIS imagery downloaded from the internet is a Level-3 data in the form of HDF (Hierarchical Data Format). This data is the result of satellite imagery from the Terra and Aqua satellites. In this research will be used MODIS image data on average monthly. MODIS image data processing in the form of the spatial distribution of sea surface temperature and distribution chlorophyll-a is done with the help of software SeaDAS 5.0.

3. **Determination of upwelling location (latitude and longitude)**
   To obtain a range of temperatures and sea surface chlorophyll-a, then used transect method both latitudinally and longitudinally through areas of strong upwelling intensity (Figure 2). The results on the processed image transect temperature and chlorophyll-a and then taken the form of numerical values in ASCII. Furthermore, the data is converted into ASCII text (.txt) with software Excel, then be graphical. Based on graphical analysis and numerical values, with the understanding that the upwelling can be known by the sea surface temperature lower than its surroundings, and chlorophyll-a is higher than the surrounding area, so the range of temperatures and sea surface chlorophyll-a in the upwelling region is determined.
4. Classification of upwelling indicator

Efforts to classify the intensity of upwelling based on sea surface temperature (SST), chlorophyll-a and upwelling index values are carried out with a few simple steps as follows:

1. A range of SST and chlorophyll-a monthly time series values are identified, from the onset of upwelling to the end of the transverse transect system,
2. The SST and chlorophyll-a time series values are calculated for the mean climatology of the month, so that the lowest, highest, average values and standard deviation are known, and are described in the figure,
3. The SST, chlorophyll-a and upwelling index statistical data are identified during the upwelling period, including the average value during the upwelling period, the standard deviations, the highest and lowest values.
4. The SST, chlorophyll-a and upwelling index ranges are classified into four categories, namely weak, moderate, strong, and very strong upwelling.

5. Identification of upwelling area

Monthly upwelling area analysis is carried out using mapping software with the following steps:

1. Process sea surface temperature data and chlorophyll-a with SeaDAS software and save the output in the form of ASCII.
2. Sort the ASCII data obtained in the order of latitude and longitude and then save it as a text extension (*.txt)
3. Interpolate sea surface temperature and chlorophyll-a data from *.txt form to shapefile to get the distribution of spatial values.
4. Classifying spatial data of sea surface temperature and chlorophyll-a concentration according to classifications that meet the upwelling criteria made or used
5. Calculates the shape of the area of upwelling according to the upwelling intensity criteria.

6. Upwelling index
Upwelling index is calculated based on longitudinal transects in South Java, based on formulations from Myrberg and Andrejev (2003) and Skogen (2004) in [14].

\[ Ul = \sum_{i=1}^{M} \sum_{j=1}^{N} w_{i,j} \Delta x \Delta y \]

\( w_{i,j} \) = Vertical Velocity
\((i,j)\) = Grid Number in x,y direction
\( M \& N \) = Maximum Grid Number for i, j, respectively
\((\Delta x, \Delta y)\) = Grid Spacing in x, y, direction in meters

The upwelling index value follows the results of [14]. The index reflects the positive vertical velocity component, the negative vertical velocity component is omitted to get the upwelling index.

3. Results and Discussions

The results on the processed image transect temperature and chlorophyll-a and then taken the form of numerical values in ASCII. Furthermore, the data is converted into ASCII text (.txt) with software Excel, then be graphed like Figure 3 and Figure 4. Based on the graphical analysis and numerical values, with the understanding that the upwelling can be known by the sea surface temperature lower than its surroundings, and chlorophyll-a is higher than the surrounding area, so the range of temperatures and sea surface chlorophyll-a in the upwelling region is determined.

Figure 3. The results of Latitudinally transects, areas where there is a decrease from the surrounding SST and increased levels of chlorophyll-a is higher than surrounding areas (areas that are restricted red box) was identified as an area of upwelling.
Figure 4. The results of longitudinally transects, areas where there is a decrease from the surrounding SST and increased levels of chlorophyll-a is higher than surrounding areas (areas that are restricted red box) was identified as an area of upwelling.

Based on the Latitudinally and longitudinally transects in locations upwelling that occurs in the south of Java to Timor (during the MODIS imagery data period 1997 to 2011) so the range of SST and Chlorophyll-a in the upwelling locations can be found. Results of Latitudinally and longitudinally transect data of SST and chlorophyll-a in the area indicated upwelling then tabulated, looking for the average value each month. The monthly mean values are then analyzed to determine the maximum, minimum and standard deviation values.

All monthly average time series data of SST transect results in the upwelling area are graphed as Figure 5. The graph is to facilitate the dividing of upwelling criteria based on SST so that the distribution can be close to balanced. Data for the division of upwelling criteria are shown in note Figure 5 about SST below.

Based on the mean, lowest and highest SST values in the upwelling area, respectively 27.1°C, 25.8 °C and 28.2 °C, and the standard deviation value is 0.4 °C, then a trial is carried out to get a balanced dividing. The results of trial and error then obtained the boundary distribution of criteria at line A of 27.3 °C, B of 26.9 °C and C of 25.6 °C. The lower the SST, it is assumed that the upwelling process is getting stronger. Next upwelling criteria are divided into four, namely weak upwelling/WA (WA ≥ 27.3), moderate upwelling /IU(26.9 ≤ IU < 27.3), strong upwelling (26.5 ≤ SU < 26.9), very strong upwelling (VSU < 26.5).

Figure 5. The SST values in the upwelling area from 1987 to 2011
Notes Figure 5 about SST:

Statistic SST (°C)
- Average Value = 27.1
- Standard Deviation = 0.4
- Higher Value = 28.2
- Lower Value = 25.8

Line limits Count
- A: 27.1 + (0.5 x 0.4) = 27.3
- B: 27.1 - (0.5 x 0.4) = 26.9
- C: 26.9 - 0.4 = 26.5

Upwelling Strength Criteria:
- Weak Upwelling (WA): WA > 27.3
- Intermediate Upwelling (IU): 26.9 ≤ IU < 27.3
- Strong Upwelling (SU): 26.5 ≤ SU < 26.9
- Very Strong Upwelling (VSU): VSU < 26.5

All monthly average time series data of chlorophyll-a transect results in the upwelling area are graphed as Figure 6. The graph is to facilitate the distribution of upwelling criteria based on chlorophyll-a so that the distribution can be close to balanced. Data for the division of upwelling criteria are shown in note Figure 6 about chlorophyll-a below. Based on the mean and standard deviation, the upwelling criteria are divided based on chlorophyll-a. Based on the average monthly, lowest and highest SST values in the upwelling area, respectively 0.64 mg/m³, 0.26 mg/m³ and 1.75 mg/m³, and the standard deviation is 0.28 mg/m³, then a trial is carried out to get a balanced dividing. The results of trial and error then obtained the boundary distribution of criteria at line A of 0.36 mg/m³, B of 0.92 mg/m³ and C of 1.48 mg/m³. The higher the chlorophyll-a, it is assumed that the upwelling process is getting stronger. Next upwelling criteria are divided into four, namely weak upwelling/WA (WA < 0.36), moderate upwelling/IU (0.36 ≤ IU < 0.92) strong upwelling (0.92 ≤ SU ≤ 1.48), very strong upwelling (VSU > 1.48),

Figure 6. The chlorophyll-a values in the upwelling area from 1997 to 2011

Notes Figure 6 about Chlorophyll-a:

Statistic Chlorophyll-a (mg/m³)
- Average Value = 0.64
- Standard Deviation = 0.28
- Higher Value = 1.75
- Lower Value = 0.26

Line limits Count
- A: 0.64 - 0.28 = 0.36
B : 0.64 + 0.28 = 0.92
C : 0.92 + (2 x 0.28) = 1.48

Upwelling Strength Criteria:
Weak Upwelling (WA) : WA < 0.36
Intermediate Upwelling (IU) : 0.36 ≤ IU < 0.92
Strong Upwelling (SU) : 0.92 ≤ SU ≤ 1.48
Very Strong Upwelling (VSU) : VSU > 1.48

All monthly average time series data of Upwelling Index transect results in the upwelling area are graphed as Figure 7. The graph is to facilitate the dividing of upwelling criteria based on the Upwelling Index so that the distribution can be close to balanced. Data for the division of upwelling criteria are shown in note Figure 6 about Upwelling Index below. Based on the mean, lowest and highest Upwelling Index values in the upwelling area, respectively 0.65 Sv, 0.49 Sv and 0.87 Sv, and the standard deviation value is 0.07 Sv, then a trial is carried out to get a balanced dividing. The results of trial and error then obtained the boundary distribution of criteria at line A of 0.62 Sv, B of 0.69 Sv and C of 0.76 Sv. The higher the upwelling index it is assumed that the upwelling process is getting stronger. Next upwelling criteria are divided into four. namely weak upwelling/WA (WA < 0.62), moderate upwelling/IU(0.62 ≤ IU < 0.69), strong upwelling (0.69 ≤ SU ≤ 0.76), very strong upwelling (VSU>0.76).

![Figure 7. The Upwelling index values in the upwelling area from 1990 to 2011](image)

Notes Figure 7 about Upwelling Index:
Statistic Upwelling Index (Sv)
Average Value = 0.65
Standar Deviation = 0.07
Higher Value = 0.87
Lower Value = 0.49
Line limits Count
A : 0.65 − (0.5 x 0.07) = 0.62
B : 0.65 + (0.5 x 0.07) = 0.69
C : 0.69 + 0.07 = 0.76

Upwelling Strength Criteria:
Weak Upwelling (WA) : WA < 0.62
Intermediate Upwelling (IU) : 0.62 ≤ IU < 0.69
Strong Upwelling (SU) : 0.69 ≤ SU ≤ 0.76
Very Strong Upwelling (VSU) : VSU>0.76
The results of the entire dividing of upwelling criteria based on SST, chlorophyll-a, and upwelling index are tabulated in Table 1.

Table 1. Final results of the distribution of upwelling criteria in the waters of the Java South Indian Ocean, based on SST, Chlorophyll-a and Upwelling Index

| Upwelling Strength       | Indicator SST (˚C) | Indicator Chlorophyll-a (mg/m³) | Indicator Upwelling Index (Sv) |
|--------------------------|--------------------|---------------------------------|--------------------------------|
| Weak Upwelling (WA)      | WU > 27.3          | WU < 0.36                       | WU < 0.62                      |
| Intermediate Upwelling (IU) | 26.9 ≤ IU ≤ 27.3  | 0.36 ≤ IU < 0.92                | 0.62 ≤ IU < 0.69               |
| Strong Upwelling (SU)    | 26.5 ≤ SU < 26.9   | 0.92 ≤ SU ≤ 1.48                | 0.69 ≤ SU ≤ 0.76               |
| Very Strong Upwelling (VSU) | VSU < 26.5        | VSU > 1.48                      | VSU > 0.76                     |

In applications to demonstrate the strength of upwelling is weak, intermediate or strong should be two classifications SST and chlorophyll-a above are used together, cannot simply stand alone, such as SST only or chlorophyll-a only. Specifically for upwelling index can be used singly to determine the upwelling criteria. The use of one parameter only SST or chlorophyll-a alone, one time would have difficulty in determining the boundary upwelling, because in a certain period of SST in the oceans could be worth a low (cold) all.

Based on the upwelling criteria in Table 1 above, we can apply to map the location of upwelling in the Indian Ocean Waters Southern Java to Timor. This criterion can serve as a barrier to determine the spatial distribution and extent of upwelling in the waters of South Java to Timor.

This criterion can only be used in the upwelling areas of the Indian Ocean Waters South Java to Timor because the input data for the dividing of criteria is only from that region. To map the distribution and extent of upwelling in other locations, it is better to make an upwelling situation at that location. If it can be made upwelling criteria by inputting data from all upwelling areas throughout Indonesia, then these criteria can be used in general for all Indonesian waters.

The Example application of mapping spatial upwelling distribution in four case climate variability based on SST and chlorophyll-a in the Indian Ocean Waters South Java to Timor, be showed in Figure 8. The picture shows the development of strong upwelling distribution in the La Nina IOD(+) incident of 2007-2008, month June until October. The extent of upwelling on June, July, August, September and October respectively 55,630.8 km³; 261,344.4 km³; 312,638.5 km³; 44,462 km³; 70,873.9 km³.

Based on the data in Figure 8, it appears the beginning of the emergence of strong intensity upwelling generally in June, this occurs related to the beginning of the eastern monsoon (Southeast Monsoon), where the Southeast Monsoon winds start to blow intensely towards the southwest along the southern coastline of Java Island to Timor Island. Eastern Season in June has been described by [15] and the emergence of upwelling in June has also been in accordance with several research results including [8], [9]. The strength of the wind determines whether the upwelling formed has strong or weak intensity. In the case of La Niña-IOD (-) strong intensity upwelling was not found (Figure 8), this happened because the blowing wind power was allegedly unable to generate strong intensity upwelling because in general the speed was weakest among the three other cases [16].
The peak of upwelling events with a maximum area distribution generally occurs in August or September. The extent of strong intensity upwelling, especially during maximum conditions, was found that the most extensive upwelling occurred when La Niña-IOD (+) amounted to 312,638.5 km², then followed in the El Niño-IOD (+) case of 160,921.5 km², and the most narrow in the El Niño-IOD (-) case of 119,000.3 km² (Figure 9b). The variability of the upwelling area appears to be closely related to the speed of the monsoon [12]. While the monsoon wind variability is influenced by ENSO and IOD, this is seen in the La Niña-IOD (+) case. In theory, the upwelling in the south of Java to Timor was weakened by the La Niña phenomenon, but a high positive DMI value (Figure 9a) had the effect of increasing the intensity of the upwelling occurring. When La Niña-IOD (+), low air pressure is in the western Indian Ocean and high air pressure is in the East Indian Ocean, this causes strong winds to blow from the eastern Indian Ocean to the west [17]. The greater the positive IOD index value, the stronger the wind will blow westward. The wind is the main driver of the upwelling process [9], [12]. In the La Niña-IOD (+) case in 2008, the wind speed from August to October showed the highest value than the other three cases [16]. Thus, it would be logical if the upwelling that occurred also had wider spatial distribution up to 312,638, 5 km², which extends from the south of West Java to Sumbawa (Figure 8). Based on statistical analysis from the initial appearance of upwelling until it reaches its peak, a very strong relationship was found between the extent of upwelling that occurs with the DMI value with a mean correlation coefficient of 0.88 (Figure 9a), while the relationship between the area of upwelling formed with SOI (ENSO index) shows a positive average correlation coefficient by 0.53 (Figure 9b). This shows that the area of upwelling in the south of Java to Timor is more influenced by the value of IOD than ENSO.

Figure 8. The mapping of spatial strong upwelling distribution in La Nina-IOD(+) event 2007-2008, based on SST and chlorophyll-a in the Indian Ocean Waters South Java to Timor (a) June, (b) July, (c) August, (d) September, (e) October
Figure 9. (a) Comparison of DMI variability patterns and upwelling extents, correlation value (r)=0.88; (b) Comparison of SOI (ENSO Index) variability patterns and upwelling extents, correlation value (r)= 0.53

Figure 10. (a) The average Dipole Mode Index in four case climate variability, (b) Average upwelling area in four case climate variability

4. Conclusions

The existence of links between upwelling strengthened or weakened by growing or shrinking range of SST and chlorophyll-a, be evidence that the SST and chlorophyll-a are not only as a qualitative indicator of the presence or absence of upwelling but further, this range can be as an upwelling strength indicator.
Based on the range SST, chlorophyll-a, and upwelling index, the upwelling phenomenon in southern Java to Timor could be made classification become four criteria: weak upwelling (WU), intermediate upwelling (IU), strong upwelling (SU), very strong upwelling (VSU). Based on the upwelling criteria, we can apply mapping the location of upwelling, to determine the spatial distribution and extent of upwelling in Indian Ocean waters southern of Java to Timor. Two indicators of upwelling SST and chlorophyll-a are more accurate in the application if be used together.

The variability of ENSO and IOD significantly effected growing and reducing the range of upwelling. ENSO and IOD significantly affected growing and reducing the range of upwelling, but the IOD index much greater effecting than ENSO index (SOI).

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