Upwelling index along the South Coast of Java from satellite imagery of wind stress and sea surface temperature

Y Naulita, R E Arhatin and Nabil
Department of Marine Science and Technology, IPB University Bogor, Indonesia
*e-mail: naulita@ipb.ac.id

Abstract. Upwelling Index which is processed from satellite imagery of wind stress and Sea Surface Temperature (SST) were examined to describe upwelling and its dynamics along the southern coast of Java. Analysis in September as the peak of upwelling shows that the commonly use of Ekman Transport-based Upwelling Index mostly shows higher values on the western part of south coast of Java as the alongshore wind stress is stronger to the west. But on the contrary, the SST-based Upwelling Index shows a relatively intense and persistent upwelling on the eastern part of south coast of Java and strengthened in El Nino year of 2015. The intense upwelling is indicated by the lowest value of SST minimum and the maximum value of thermal gradient SST up to 75 km off shore. Thus, for upwelling areas that are not predominantly induced by offshore Ekman Transport, the dynamics of upwelling would be better seen through an SST-based upwelling index. The use of both upwelling indices, will complement each other so that upwelling and its dynamics can be precisely understood.

1. Introduction
Upwelling areas on the coast are fertile areas with high primary productivity that support fisheries of pelagic species. Freon [1] stated for Eastern Boundary Upwelling Ecosystems which cover only 1% of the world's sea surface, contribute to 20% of global fish production. In Indonesia waters, the west coast of Sumatra to the south of East Nusa Tenggara are one of which has been identified as the intense upwelling areas. Fish catch data from some harbor in south coast of Java reveal the dominant of large pelagic fish such as skipjack tuna, blue marlin etc. have landed in these fish harbors. During the Southeast Monsoon (SEM), high amounts of chlorophyll a in the surface waters are correlated with high catches of cakalang [2]. Hendiarti [2] also reported from Banyuwangi harbor, a high abundance of small pelagic schooling fish like *sardinella* in upwelling areas off the southern coast of East Java, which is characterized by cold water and high surface chlorophyll.

The upwelling phenomena along the south coast of Java is a form of recurring upwelling evolution each year that is affected by seasons and climate [3][4][5], and in normal year, the upwelling center moves westward and toward the equator during the SEM [5]. As described by Ekman (1905) [6] and later by Bakun (1973) [7], the relatively cold and nutrient-rich water rises along the coastal shelf edge as a result of the alongshore winds forcing. Theoretically, this wind will cause horizontal currents to move at sea level, away from the coast by Coriolis force, causing a difference in sea level height. This condition will cause vacancies on the beach side so that the water mass in the lower layer will rise to the upper layer by the Ekman pumping process. Quantification of the upwelling intensity can be done by calculating the Coriolis force that induce the cross-shore Ekman transport. Thus, the coastal upwelling...
For the purposes of synoptic and continuously monitoring of upwelling areas, remote sensing technology is needed because through this technology, it is easier to obtain data related to spatial and time changes of upwelling parameters. Some methods have been developed to understand upwelling phenomena using wind data obtained from satellite imagery [8] and based on Sea Surface Temperature (SST) between the coast and offshore in studied upwelling areas [9][10].

The application of both upwelling indexes, the Ekman Transport upwelling and SST index methods in Indonesian waters will be very useful for improving how to study upwelling and its dynamics. As one of area experience intensive coastal upwelling, our study area is between 6.5 – 10° S and 105 – 115° E along the south coast of Java (figure 1). The aim of this study is to examine the method of determining the upwelling area by calculating the upwelling index and its correlation with SST and chlorophyll-a imagery data. For that purpose, we explored the detailed upwelling indexes inside three upwelling centers, south coast of West Java (hereafter WUC) at 7.3 – 8.8° S and 106.8 – 108.5° N, of Middle Java (MUC) about 7.7 – 9.2° S and 109.7 – 111.3° N and of East Java (EUC) about 8.2 – 9.6° S and 113.2 – 114.6° N. The three upwelling centers were chosen as the low SST (21.4 to 25.6 °C) is often observed along the coast during the SEM [6]. The results of this study are expected to provide benefits in determining the upwelling area and its dynamics by using more accurate upwelling indexes.

![Figure 1. The study area along south coast of Java and its bathymetry from General Bathymetric Chart of the Oceans (GEBCO).](image)

2. Datasets and methods

2.1. Datasets
This research used datasets derived from satellite imagery of wind stress, SST, chlorophyll-a concentration of 2006 – 2017 for describing upwelling phenomena along south coasts of Java (Table 1). And focusing in the normal year of 2014 and El Nino year of 2015 for exploring the upwelling indexes inside the three of upwelling centers (WUC, MUC and EUC).
Table 1. Datasets used in this research and its sources.

| Datasets                        | Sources                                                      |
|---------------------------------|--------------------------------------------------------------|
| Wind stress of QuickSCAT        | http://marine.copernicus.eu/                                |
| SST of AVHRR                    | https://oceancolor.gsfc.nasa.gov/atbd/sst/#sec_5             |
| Chlorophyll-a of Aqua-MODIS     | https://oceancolor.gsfc.nasa.gov/atbd/chlor a/               |
| Bathymetry of GEBCO             | http://www.gebco.net/                                       |

2.2. Methods
We used two kind of upwelling indexes, Ekman Transport Upwelling Index and SST-Upwelling Index. The first one as the forcing of coastal upwelling and the second one as the ocean response to upwelling forcing.

2.2.1. Ekman Transport-based Upwelling Index (ET-UI). This method based on index of upwelling calculation by Bakun (1973) [7] that developed from Ekman Theory of Upwelling (Ekman, 1905) [6]. Bakun calculated the index using daily wind images with resolution of $1/4^\circ$ and Ekman Transport is derived from [10]:

\[ M_x = \frac{\tau_y}{f} \]  

where: $M_x =$ Cross-Shore Ekman Transport  
$\tau_y = \rho C_D W v =$ wind stress  
$W =$ wind speed (ms$^{-1}$)  
$v =$ component of wind speed on y-axis  
$f =$ Coriolis parameter

Then the Upwelling Index based on Ekman Transport (hereafter ET-UI) is calculated from:

\[ ET – UI = \frac{1000 \ m \ coastline}{1025 kg/m^3} \ (m^3/s/1000 \ m \ coastline) \]  

Negative (positive) Ekman’s transport offshore is upwelling (downwelling).

2.2.2. SST-based Upwelling Index (SST-UI). This index based on thermal difference of minimum SST \((SST \ min)\) in the coastal to maximum SST \((SST \ max)\) in the offshore. It uses to qualify the coastal cooling effect of the upwelling. We choose three different distances from coastal: 25, 50 and 75 km.

\[ SST \ gradient = SST \ max \ offshore – SST \ min \ inshore \]  

\(SST \ min\) is defined as the minimum SST recorded in the coastal band from the coast up to the distance of the continental slope, \(SST \ max\) is defined as the offshore temperature where the influence of the upwelling is supposed to be not significant. \(SST \ min\) and \(SST \ max\) are processed from the 8 days SST imagery.

2.2.3. Wind stress. Determination of wind pattern was derived from QuickSCAT satellite (producer agency IFREMER and producer institution CERSAT) from 2006 to 2017. Data was downloaded as netcdf file with spatial resolution of 1.50 km x 1.50 km. The data is used for determining spatially and temporally wind direction and its strength variability, and along shore wind stress as well. The process was conducted by using Pyferret v6.96 while the wind rose was drawn by WRPLGOT view-freeware version 7.0.0.
In the purpose of calculation of ET-UI, before it was used, the wind orientation was rotated as the Java island is not exactly in E-W orientation. The rotation using equation by Thomson and Emery (2014):

\[ u_r = u \cos \theta + v \sin \theta \]  
\[ v_r = -u \sin \theta + v \cos \theta \]

where \( u \) = E-W component of wind  
\( v \) = N-S component of wind  
\( \theta \) = angle of wind and the shoreline

For determination of the ET-UI inside the three upwelling centers, the wind imagery was cropped for that areas, then separated between land and ocean. Determination of the angle of shoreline needs map of isobath that downloaded from GEBCO with 30 seconds grid for latitude and longitude.

2.2.4. Seas Surface Temperature (SST). The 8 days SST imageries from 2006 – 2017 that estimated from MODIS with resolution of 1 km. The algorithm for SST Mcmillin & Crosby.

\[ SST = T_{w4} + 2.702(T_{w4} - T_{w5}) - 0.582 - 273 \]

where: \( T_{w4} = \) temperature air band 4  
\( T_{w5} = \) temperature air band 5

2.2.5. Chlorophyll-a. The chlorophyll-a imageries were derived from CHLA-OC3 using MODIS algorithm with spatial resolution of 1 km. Inside the three upwelling centres are further explored by calculation the monthly variation chlorophyll-a concentration per surface areal extent (km\(^2\)) in three values: > 1 mg/m\(^3\), > 3 mg/m\(^3\) and > 5 mg/m\(^3\).

3. Results and discussion

3.1. Upwelling along the south coast of Java

From previous studies, we know upwelling along south coasts of Java occurs in Southeast Monsoon (SEM) from June to the middle of October [3][4][5]. The peak is in September so that we examined the upwelling intensity in a more detail inside that month. In September, the upwelling area with low SST is clearly observed along south coast of Java. This coastal upwelling was generated by strong alongshore wind stress where the south-easterly wind blow from Australia with the strength of 5.7 to 8.8 ms\(^{-1}\) in September. The alongshore wind stress becomes stronger to the west that together with latitudinal changes in the Coriolis parameter, migrates the upwelling center westward with the speed of 0.2 ms\(^{-1}\) [5].

The upwelling phenomena along the south coasts of Java also corresponds very well to high standard deviation of monthly average of SST, negative value of Surface Height Anomaly (SSHA) and high concentration of chlorophyll-a. From satellite-derived chlorophyll-a data, we can see that higher concentration was confined in nearly along shore of south coast of Java but later we found the values and its trend of monthly variation of concentration chlorophyll-a in three upwelling areas, WUC, MUC and EUC, are different. To compare the upwelling intensity in normal year of El Nino and El Nino year, we examined the three upwelling centres for September 2014 and 2015.
Figure 2. SST imagery along south coast of Java (above) and the alongshore wind stress imagery (below) indicating upwelling occurs in September 2014. Inset: wind rose in September 2014.

Figure 3. Chlorophyll-a concentration along the south coast of Java during September 2014. The three upwelling centres (WUC, MUC and EUC) are shown by boxes.

Intensity of upwelling often indicated by high concentration of chlorophyll-a because the upwelled water mass is nutrient-rich water so that trigger a high phytoplankton growth. Figure 3 shows monthly
variation of the high concentration of chlorophyll-a that indicated by higher than 5 mgm\(^{-3}\) per km\(^2\) of surface waters. We have examined for three concentrations as mentioned in sub-subsection method (>1 mgm\(^{-3}\), > 3 mgm\(^{-3}\) and > 5 mgm\(^{-3}\)) but does not show noticeable different trends, so that we choose the highest concentration (>5mgm\(^{-3}\)) to describe the evolution of upwelling along the south coast of Java. In normal year, the peak of upwelling clearly seen occur in September. The highest value is found in WUC and decreases to eastern part of south coast of Java. In September, the area of high chlorophyll-a concentration inside EUC covers an area of ~ 2,715 km\(^2\), while inside MUC and WUC decreases to 2,273 and 1,545 km\(^2\) respectively.

**Figure 4.** Monthly variations of concentration of chlorophyll-a above 5 mgm\(^{-3}\) per areal extent (km\(^2\)) of surface waters within the three upwelling centres (WUC, MUC and EUC) along the south coast of Java during 2014 (above) and 2015 (below).

In general, the trend of monthly variations of high chlorophyll-a concentrations inside the three upwelling centers looks similar. The area of high chlorophyll-a concentration gradually increases started at June-July then fourfold to 1,200 km\(^2\) in August for intense upwelling areas, and it reaches a maximum
value in September. Chlorophyll-a concentration in the EUC persistently greater and more permanent compared to MUC and WUC. It becomes obvious that upwelling in the southern waters of eastern Java is stable with strong intensity, and occurs throughout the year (stationary upwelling) while in southern waters of western Java are seasonal (seasonal upwelling) [11][12][13].

The ocean dynamics in northern part of Indian Ocean also influence the upwelling dynamic along the south coast of Java. Total water mass transport to the south is not only due to zonal wind friction but also due to the axis of the South Equatorial Current (SEC) which is closer to the southern coast of the eastern part of Java than to south coast of the western part of Java in SEM so that upwelling is more intensive on the south coast of East Java [13]. Wyrtki [14] estimated about 2.4 Sv of upwelling water in this area contributing to SEC and the upwelling seemed to develop along the boundary of the Java Coastal Current and SEC.

Monthly variation in extreme El Nino year of 2015 reveals in even stronger intensity. As stated by [4][5][15], El Nino and/or Indian Dipole Mode (IOD) may also maintain the upwelling become stronger and persists longer. The high concentration of chlorophyll-a abruptly started to increase from earlier month, April in the MUC and EUC and delay to June in WUC. The upwelling’s peak in EUC extent to October 2015 with almost doubling the area of high concentration (>5 mgm⁻³) per km² surface waters. Noted that this very obvious changes were seen only at EUC. Susanto [5] speculated inter-annual upwelling variability that occurred in southern Java was related to El Nino through Indonesian Throughflow (ITF) and easterly wind anomalies. During the El Nino episode, upwelling in southern Java lasted longer (until November) and expanded (to near the equator). The role of ITF is likely to have a major influence on the large increase of high surface chlorophyll-a occurring at EUC because located near to the ITF outflow in Lombok Strait. From a wave–tide–circulation coupled model, Kuswardini and Qiao [15] found about 55 to 65% formation of upwelling in eastern part of south coast of Java is caused by ITF.

The differences of upwelling conditions revealed by ET-UI to high concentration of chlorophyll-a motivated us to explore whether the dynamics of upwelling are sufficiently descripting by ET-UI or we should add some other indexes so that the method of upwelling identification can be more accurate. Then we tried to explored the two upwelling indexes, that is ET-UI and SST-UI.

3.2. The dynamics of upwelling as shown by upwelling indexes

It’s common to use ET-UI to identify upwelling area like shown in figure 5 for September 2014 and 2015. The values of ET-UI in the EUC is the smallest among the three upwelling centers, even in El Nino year of 2015. Thus, we would have thought the EUC is a weak upwelling area. Purba [13] speculated that upwelling along the south coast of Java showing a different behavior between the eastern and western coast. Even though the orientation of the coast is constantly in E-W where western area usually presents more intense zonal winds while coastal upwelling is stronger in the eastern area. This condition obviously seen through the ET-UI values but the ocean response shows the opposite as revealed by high chlorophyll-a concentration inside the three upwelling centers.

To support this finding, then we analyzed satellite derived SST data to find the SST min on coastal area as a cooling effect of the upwelling and SST-UI inside each upwelling centers. Firstly, we compared the SST min values among the upwelling centers in El Nino year of 2015 in order to contrast it, then we analyzed for 11 years of SST data during September 2006 to 2017. The histogram of SST min in September 2015 is presented in figure 6. The SST min in EUC is lower than that in MUC and WUC with average of 23.10 °C. This relatively cold water origin from below that pumped up by coastal upwelling. Therefore, the stronger vertical velocity, the colder surface water found on coastal. By using wave-tide-circulation model, [15] found the annual averaged values of upwelling is 1.06 x 10⁻⁵ ms⁻¹ for south of East Java while much weaker in south of West Java, about 3 x 10⁻⁶ ms⁻¹. They also found the difference behavior of the western part upwelling area to eastern part. The vertical velocity in the eastern part is quite steady and strong while variable in the western part.
Figure 5. Ekman Transport Upwelling Index (ET-UI) along the south coast of Java during September 2014 and 2015. The position of the three upwelling centres (WUC, MUC and EUC) are shown in light green boxes.

Figure 6. Histogram of SST min inside upwelling centre of western part (WUC) (left), middle part (MUC) (middle) and eastern part (EUC) (right) along the south coast of Java during September 2015.

The same feature was also shown in a longer data series, September 2006 to 2017 (figure 7). The median of SST min in WUC is 25.02 °C with the range of SST min of 24.52 – 25.63 °C, a bit higher compared to median of SST min in MUC, 24.73 °C with the range of 24.21 – 25.35 °C. In the most intense upwelling center of EUC, median of SST min decrease to 24.67°C with a smaller range of SST min of 24.12 – 25.03 °C. It’s clearly reveals the upwelled-water mass in EUC stronger than that in others.
Secondly, we measured the thermal difference between SST min along the coast on the shelf of 200 m to a certain distance where the SST up to a maximum temperature in offshore (SST max). The assumption for the distances of SST max that is the upwelled-water no longer affected in the distances [10]. Using 3D hydrodynamic model of HAMSOM (Hamburg Shelf Ocean Model), [12] found that in the intense upwelling area in the south of East Java, vertical current reaches 61 km from coast to offshore, therefore we used distances of 25, 50 and 75 km, as presented in figure 8 for MUC.

Figure 8. The distance of SST min to a certain km to offshore inside upwelling center along the south coasts of Middle of Java (MUC) during September 2014. ● SST min, ● SST max of 25 km from SST min, ● SST max of 50 km from SST min, ● SST max of 75 km from SST min.

The average of thermal difference between SST min on coastal to some distances of SST max to offshore (SST-UI) for three upwelling centers is presented in Table 2. The higher the SST-UI value, the more intense upwelling occurs. Again, the EUC shows a larger gradient of thermal difference than that in MUC and WUC, indicating an intense upwelling center.
Table 2. Average SST-UI inside the West Upwelling Center (WUC), Middle Upwelling Center (MUC) and East Upwelling Center (EUC) along south coast of Java during September 2015.

| Upwelling Center | Offshore Distance (km) |
|------------------|------------------------|
|                  | 25         | 50         | 75         |
| WUC              | 1.65       | 1.79       | 2.19       |
| MUC              | 2.05       | 2.18       | 2.31       |
| EUC              | 1.87       | 2.36       | 2.50       |

Then we present SST-UI boxplot for a longer satellite derived SST data, September 2006 to 2017 (figure 9). For three distances are used in this study, median of WEC always lower than others indicated that the cooling effect from weaker upwelled-water only caused thermal difference of 0.86 °C in distance of 25 km offshore, 0.98 °C in distance of 50 km offshore and 1.11 °C in distance of 75 km offshore. On the contrary in a steady and strong vertical velocity in eastern part [15], inside EUC, the thermal differences are 1.35, 1.45 and 1.46 °C respectively and getting smaller inside EUC: 1.30, 1.36 and 1.39 °C respectively.

Figure 9. Boxplot of SST-UI values inside the three upwelling center (MUC, MUC, and EUC) for 25 km (left), 50 km (middle) and 75 km (right) to offshore along the south coast of Java during September 2006 to 2017.

Thus, the SST-UI agreed well with previous study about upwelling and its dynamics in along south coast of Java. The difference that revealed by ET-UI probably because the upwelling mechanism is not primarily caused by wind, but also by the ITF and other current system in eastern part of Indian Ocean. As Wyrtki [14] mentioned that SEC and SJC determining the occurrence of upwelling in south of Java.

4. Conclusion
The use of Ekman Transport Upwelling Index would be more appropriate if the main forcing of upwelling mechanism is predominantly caused by alongshore wind stress. In along south coast of Java, where the upwelling and its dynamic more affected by current system, the SST based-upwelling index is more precise to describe its dynamic.

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