SEASONAL PATTERN OF WIND INDUCED UPWELLING OVER JAVA-BALI SEA WATERS AND SURROUNDING AREA

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Abstract. The influence of monsoonal wind to coastal upwclling mechanism which is generated by Ekinan transport was studied here by analyzing wind stress curl (WSC) distribution over Java - Bali sea waters and its surrounding area. Surface wind data were used as input data to calculate curl of wind stress in barotropic model. Confirmation with Corioli effect in the Southern Hemisphere, it could be known that negative curl value has relation with vertical motion of sea water as resulted by Ekman transport. Results of analysis showed that negative curl near coast over Java Sea which is stretching to Lombok Sea occurred in December to April when westerly wind of the North West Monsoon actives. It can be guidance and related with season of coastal upwclling in the region. Reversal condition, the occurrence of coastal upwelling in the south coast of Java island related with the negative value of WSC that occurs since easterlies wind take-place in May to August as a part of South East Monsoon episode. Generally, upwelling occurrence in the field of study is a response to the Monsoon circulation. This study with related data such as sea surface temperature, chlorophyll concentration and mixed layer depth that derived from satellite imaging data National Oceanic and Atmospheric Administration - Advanced Very High Resolution Radiometer (NOAA-AVHRR), Aqua'Modis and Sea viewing Wide Field-of-view Sensor (Sea WiFS) shows a magnificent confirmation pattern. So applying WSC to recognize upwelling zone's alternatively way as climatic approach to maps potential fertilizing of sea water in maritime-continent Indonesia.

Keywords:coastal upwelling. Ekman transport, Java-BaliSea,monsoon circulation, upwelling.

1. Introduction

Indonesia region, geographically, consists of land and water area and is known as maritim-coniinent which has specific meaning in the atmospherics and oceanic sciences. Beside of its position near equator and wedged in the two large ocean, this region is often pictured by mountain range, All of that description has important meaning for regulating regional and global circulation system. As a tropical region that receive more sun's radiation, its strategic location will put in order and influence to the circulation that always formed in the atmosphere and ocean, including air mass and other particles along the latitude-longitude (Siswanto, *et al.*, 1999). Its shape showed by existence of wind, temperature, moisture and air pressure that related to physical atmosphere phenomenon in their scale, time and space. Similar to the atmospheric system, the surface oceanic circulation as generated by the air-sea interaction that appeared in form of current or wave or mass transport describing the heat exchange entire sea and ocean. In the same manner as atmosphere, water condition in the sea was defined by physical characteristics of sea water (density, temperature and salinity) that related to the energy content of the sea.

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Physical phenomenon of water of Ihe sea are influenced by various factors, one of the most important is wind. Monsoonal wind as environmental parameter gives important rule as generating force for the large scale fluids flow in Indonesia sea waters. Because of the unique position - between two of continent and two of great ocean - weather and climate of this region would be influenced by monsoon that repeated in every year, as well as an archipelago that passed by Indonesia Through Flow (Gordon, 2005). In addition to those, this region also affected by global phenomenon like El Nino Southern Oscillation (ENSO), La Nina and Indian Ocean Mode that regulating the air-sea interaction along tropical Indian-Pacific ocean.

Over the sea. wind blows and drags onto the water surface (wind stress) causes sea motions in horizontal and vertical direction. In horizontal direction, il generates cyclonic and ami cyclonic pattern which is manifested as sea surface current, while in the vertical one. a column of water flows as up motion (upwclling) or sink (downwelling) as a complex circulation.

Sea current that manifested the general characteristics of Indonesia sea water is current that generated by wind. It can occur in Ac synoptic scale as well as mesoscale when surface wind blows in a main direction (prevailing wind) above the water. In the maritime continent, tropical-seasonal characteristic of wind situation is followed by is surface current. Monsoonal wind that develops in the Asia and Australia continents aad blows above maritime continent with returning twice a year, is dominant factor that influences ocean surface circulation in the region (Wirtky, 1961). Climatologically, this field of study, Java - Bali sea waters area, is part of Indonesian tropical climate with strong monsoonal type that affected surface and sea weather (Siswanto, 2006).

Monsoonal type over Java Island and surrounding areas was indicated by the flow of wind circulation that blows permanently for one of specific period (min. three months) and the followed period is in the opposite direction with the transition periods put in between. The north-east monsoon (Asian monsoon), which dominates the circulation over the Indonesian archipelago from about December to March, gradually changes into north-westerly wind near the equator, especially in Java to Nusatenggara, it is often called the 'west' monsoon, or as it brings more water vapor and a large part of the total rainfall then known as the 'wet' monsoon that had peak in December to February. Meanwhile, the south-easterly wind from Australian Continent to equator, which prevails from about June to September, attributed by less water vapor and known as dry season that reached maximum in June - August. During the two inter-monsoon periods of March to May and September to November, winds are variable and generally quite weak, therefore, local factors control the distribution of air mass and precipitation (McGregor and Nieuwolt, 1998).

In the ocean surface, sea current flow almost the same as direction of wind regime that mentioned above. However, the currents in the deep sea more influenced by large scale ocean circulation (the great conveyor belt) or other physical properties like temperature gradient, salinity and pressure.

This paper will present the influence of the surface wind to mass transport of the sea particularly identifying vertical motion of water (upwelling) in the ekman layer over Java - Bali sea water and surrounding area.

2. Upwelling: Physical Mechanism

Upwelling refers to an oceanographic phenomenon that pictured ascending of a water column into surface layer of the sea replaced surface warm water. Although poor oxygen, water from the deep part was rich in nutrition including nitrate and phosphate as a result of decomposition processes of organic matter which occurred below a surface. If the rich nutrition water reached into euphotic layer, the overflow nutrition will stimulate phytoplankton growth which becomes basic sequences of fish's food. Consequently, upwelling location was fertile zone offish (Wyrtki, 1961; Ilahude, 1970; Pariwono *etal*, 1986).

The theory which is commonly accomplished reference to describe upwelling phenomena was Ekman Pumping (Sverdruv *et ai*, 1964). Ekman (1902) proposed his own state where he considered that the sea surface as a flat layer without horizontal pressure gradient and internal friction was neglectfully, so the motion eauation can be rewritten as:

$$\frac{1}{\rho}\frac{\partial \tau_x}{\partial \tau_z} = -fv \qquad \frac{1}{\rho}\frac{\partial \tau_y}{\partial \tau_z} = +fu \qquad (1)$$

where ρ and f were Corioli parameter, u and v stated zonal (east-west) and meridional (north-south) current, τ_x and τ_y stated zonal and meridional wind stress.

If actively forcing onto the surface is wind stress only, then by integrating equation (1) from the surface, z = 0 to deep -z, where no force of wind stress affected within the water, therefore we get mass transport equation as :

$$\tau_x = -M_y f \qquad \tau_y = +M_x f \qquad (2)$$

with,

$$M_x = \int_0^z \rho u dz \quad \text{and} \quad M_y = \int_0^z \rho v dz$$

These equation showed that water transport caused by wind stress have right hand side respect to wind direction in the northern hemisphere and left hand in the southern hemisphere.

Layer from the surface to the deep which is defined above named as Ekman Layer. The vertical current speed profile within was gained by stated τ_x and τ_y into eq. (1) in form of eddy viscosity, thus

$$A_z \frac{\partial^2 u}{\partial z^2} = -fv \quad ; \quad A_z \frac{\partial^2 v}{\partial z^2} = +fu \qquad (3)$$

where A_z is eddy viscosity coefficient.

The solution of these equations resulted current speed profile in the spiral shape, where for northern hemisphere, surface water take a right side route of wind direction as shown in Figure 1.

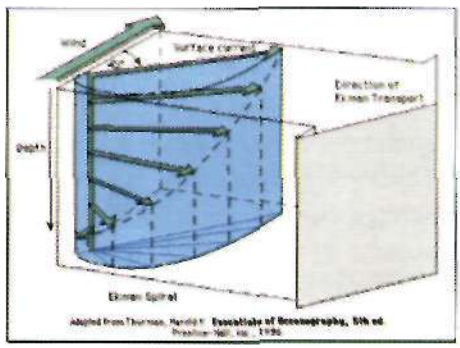

Figure 1. Ekman spiral in the northern hemisphere (a//erThurman, 1996).

The influence of Corioli effect to the wind circulation system over Indonesia region cause wind vector has tend to make rotational flow that resulted by variation of direction and speed of wind field.

Thus, this also affect on the wind stress field and resulted vorticity field at the sea surface that defined as (Stewart, 2005):

$$k.\nabla \times \tau = curl\left(\tau / f\right) = \frac{\delta(\tau_y / f)}{\delta x} - \frac{\delta(\tau_x / f)}{\delta y}$$

$$\text{or} \quad curl(\tau) = \frac{\delta \tau_y}{\delta x} - \frac{\delta \tau_x}{\delta y} \qquad (4)$$

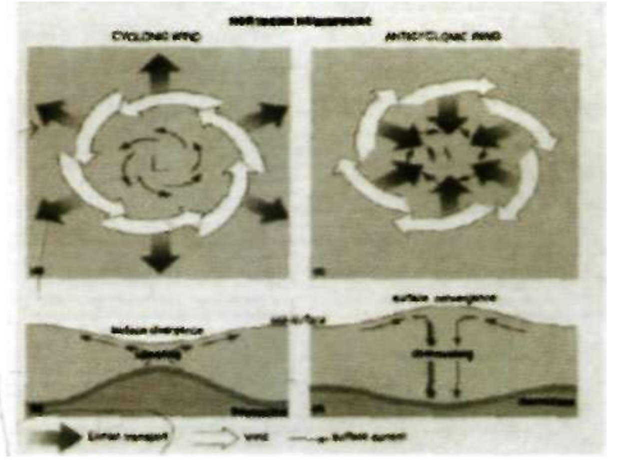

Figure 2. Conceptual scheme of upwelling mechanism caused by wind stress and surface divergcn flow (Tomsczak *et ai,* 1994).

Divergence sea surface flows induced by WSC will cause upwelling (Figure 2). Because of conservation law (continuity equation) requires vertical flow to substitute transferred water. Upwelling occurs as water response to the wind as well as the complexity effect of below surface friction, stratification, local current, topography and offshore circumstance. Easiest way to recognize upwelling zone is in a specific alongshore where wind blows caused water moves avoid the coast.

According to Ekman theory, wind stress will influence to rotate the water into left side in the southern hemisphere. The maximum upwelling appears while the wind blow parallels to the coast. So by concerning wind chart system and zone of vertical motion in the water, it is generally possible to estimate upwelling zones.

Some parameters have been used in oceanic sciences to identify its location in Indonesian waters. Firstly, Veen (1953) and Wirtky (1961) identified the upwelling occurrence in Banda Sea and Makassar Strait by temperature data and salinity *(in* Ilahude, 1970). Susanto and Gordon (2001) added ekman pumping indicator and sea level anomaly of Banda Sea. Recently, some researches take advantages and many useful of remote sensing technologies for deriving the data such us NOAA-AVHRR for sea surface temperature, TOPEX/ POSEIDON altimetry satellite for sea surface height and SeaWiFS for chlorophyll concentration.

Comprehensive and complete information of upwelling zone cover Indonesia region still less compared to larger covered area of waters and its great potential.

3. Methods

3.1. Data

This paper for domain interest of Java Island surrounding waters were use data such as:

- Surface wind 10 m Numerical Weather Prediction (NWP) Data (April 2005 - July 2006) as product of Global Forecast System (GFS) in GRIB formatted from National Weather Services -NOAAUSA. The data were used for calculating computationally of surface current and WSC in the barotropic model. The computational results were analyzed as spatial map using spline method by Arc View ver. 3.3.

- Sea surface temperature (SST) data is derived from NOAA/AVHRR channel 16 from LAPAN's Weather and Environmental Satellite Receiver and

Terra Aqua/MODIS Satellite Image, Chlorophyll-a is derived from merger SeaWiFS and MODIS (available at http://seadas.gsfc.nasa.gov/). Image processing for derived SST using split windows function of McMillin and Crossby method by ER Mapper software ver. 6.5.

3.2. Computational Scheme

Ekman Pumping which is derived by WSC approach based on bulk aerodynamic formula where wind vector was sundered into both components: zonaly (Tx) and meridionaly (Ty) (Blanc *et al*, 2000; Bakun et al., 2001) where:

$$Tx = uV \qquad Ty = vV$$

u, v were zonal and meridional wind component, while V is value of horizontal wind ($V^2 = u^2 + v^2$ and $V^4 = Tx^2 + Ty^2$).

Wind Stress computed as formula:

$$\tau_x = \rho_a . C_d . u|V| = \rho_a C_d . T_x$$
$$\tau_y = \rho_a . C_d . v|V| = \rho_a C_d . T_y \qquad (5)$$

where τ_x and τ_y were zonal and meridional wind stress, ρ_a was air density assumed constantly $\rho_a = 1.25$ kg/m^3.

The vertical component curl τ at the surface described as k.∇ x τ each grid (x,y) computed as finite-centered-difference numerical scheme:

$$k.\nabla \times \tau = \frac{\tau_{y(x+1)} - \tau_{y(x-1)}}{2\Delta x} - \frac{\tau_{x(y+1)} - \tau_{x(y-1)}}{2\Delta y} \qquad (6)$$

where, $\tau_{y(x+1)}$ and $\tau_{y(x-1)}$ represent the northward stress component one grid location to the east and one grid location to the west respectively, while $\tau_{x(y+1)}$ and $\tau_{x(y-1)}$ represent the eastward stress component one grid location to the north and one grid location to the south respectively, and Δx and Δy are the respective grid mesh length in the zonal and meridional coordinate direction (corresponding to 5 by 5 minutes latitude and longitude). Corioli effect to latitude variation was neglected in this scheme, assumed of less in value. Surface current and wind outputs were produced by BMG-WINDWAVE05 computation.

This paper studied only figuring field of study in term average seasonally where dry season represent by June-July-August (JJA) while the wet season represent by December-January-February (DJF) and in case we toqk January as a peak of wet season and July as the opposite one.

4. Result and Discussion

4.1. Air-Sea Interaction

The two different of seasonal wind patterns over field of study can be seen from the pattern of surface wind field model outputs in January and July (Figure 3A-B) which are known as peak of westerly wind season and as peak of easterly wind season.

In January, westerly wind speed 5 to 15 knot of wind surface shown as a main circulation over Java Island and its surrounding area, generally wind blows in the west direction over the Java Peninsula and west south west direction in the Indian Ocean. Wind blows stronger over the sea than inland as well as coastal area. It has been proven that the air circulation over the region is stronger over oceanic region than over the land. The contrary condition has been seen in July where wind blows in the opposite direction from east - south easterly over the region from Australian continent to equator, stronger easterly still appeared over Indian Ocean reached 25 knot of speed while the other region in the main area was lower than 20 knot. The description of atmospheric circulation in the peak of different season above had shown that zonal component became dominant than meridional one. Thus, wind stress would also tend to in the zonal direction.

The main pattern of atmospheric circulation mentioned above coincides with surface current field as a result of sea surface-wind interaction. Figure 3C-D described general pattern of surface current in January (westerly monsoon) and July (easterly monsoon) representatively. Generally, surface current had same pattern as wind circulation with accompanied by cyclonic patterns in the northern Java island waters (Java Sea) and anticyclo.nic pattern in the southern part during westerly monsoon, while it seemed to be vice versa during easterly monsoon. The contra flow current that appeared alongshore is being supposed as a consequence of eddy (cyclonic/nnticyclonic) pattern of the current as well as response to morphological affect. Ill January, alongshore contra How current in the north of island was formed by cyclonal vortexes that exist in the north of central Java, north of Madura Island and in Lombok Sea, while in the south of island caused by antkyclonal vortex that exists in the south of Java Island. Meanwhile, in July, the condition of surface current of the main area rented to be opposite as anlicyclonal vortex on these location in the north of island and cyclonal vortex in the south of island.

Furthermore, from WSC analysis in Figure 3E-F, these are being supposed that WSC as identification of sea surface vorticity due to wind induced upwclling/downwelling in the upper layer of sea waters have its own characteristics due to monsoon circulation. ws a convention here, wind induced upwelling was signed by negative value of ttirl (blue shade) while the positive one (red shade) was identifyingdownwelling.

In January, upwelling were identified in Java Sea along coastline and in particular seemed to be stronger in the north of Central Java to such an extent to Lombok Sea where the cyclonal patterns of surface current exist. Upwelling also appeared in the open sea of Indian Ocean soutli of East Java. Meanwhile, downwelling occurred in the south of island along coastline and seemed to be stronger in the area where anticyclonal patterns exist. In July, coastal upwelling appeared in the south of island and identified to be strong in the south of" East Java and West Java while upwelling in the open sea can be seen appeared in the south of Lombok - Nusa Tenggara Barat. In the other hand, downwelling in the Java Sea occurred in weak intensification. We suggest that this related to the wide of Java Sea as well as extension of upwelling existence in the southern Borneo.

The cyclonal/anticyclonat pattern most likely play role to the upwelling/ downwelling occurrence in those areas that quite far from coastline as mentioned above. Its mechanism probably like a cyclonic pattern of gyre in the wide ocean that makes surface layer divergence and thus driving water flow out which is known as open sea upwelling. This probably explains upwelling in the open sea and their processes, in addition to coastal upwell ing mechanism.

Derived observational satellite image data from SeaWiFS/Modis for chlorophyll-a concentration (Figure 6A-B) shows pattern likewise, where in January, it can be seen that concentration in the entire of Java Sea present abundantly. But the special case appeared in July where chlorophyll-a concentration in the most of region seemed to be excessive. Despite extension of chlorophyll concentration in the south of island along coastal area became widely, that one in the Java Sea still remained wealthy. This probably has a relationship with the weaken downwelling as mentioned before.

According to Aqua/MODIS satellite data (Figure 4), in January, it can be seen that SST varies between 24*C-29'C with less temperature spreads in the east of Lampung and Java sea north of East Java, whereas NOAA-AVHRR image on 11/12/2005 had clarified sea surface temperature tend to be warm in range 27'C-30°C accompanied by less temperature *25^oC-26.5^0C* took placed in some locations of the north Java Island, Bali-Lombok which then be identified as upwclling zone, however, it was unevenly spreading (Figure 5). In July, monthly analysis of Aqua/MODIS image showed SST over Java Sea became warmer (28.5°C-29.5"C) rather than in south one of which SST tend to be in range 27.S°C-29.5°C especially south of Java Island's coast area. NOAA-AVHRR image on 20/07/2005 also exhibited the occurrence of less temperature 25°C-26.5°C located in south of Java, Bali-Lombok. Furthermore, these areas were identified as upwelling zone which is attributed by sea surface that being colder rather than surrounding resulted from upwelled deep waters to the surface.

Considering comparable model output to observational data above, we can Find more or less a similarity pattern between model and observation. Particularly in July of which upwelling occurred both in north or south of Java Island. Java Sea is a fissure waters area between Java and Borneo islands, and during this period, ekman pumping response to easterly wind and generates upwelling in south of Borneo therefore increase chlorophyll productivity in this area. An advanced study is needed to clearly this problem.

4.2. Seasonal Characteristics

As explained previously, we took averages of three months analysis to represent its seasonal characteristics and thereby the seasonal pattern. DJF period was taken for describing westerly monsoon (westerly wind) and JJA period for easterly monsoon representatively.

From Figure 7, we possible to identify that there are two types of upwelling process that signed by negative value of wind stress curl, both are upwelling that occurred nearby coastal area (so called as coastal upwelling) and upwelling that appeared in the open sea (open sea upwelling), both of them are caused by wind induced onto surface sea as physical process with unequal mechanism.

The coastal upwelling occurrence for JJA period was easily found and strongly appeared in south coast of West Java, south coast of East Java and in open sea south of Lombok and Sumbawa Island. Zonal persistence wind blows of easterly wind from Australian continent drove surface transport (Ekman) toward left side and moved the water mass away from coastal area. Lacking mass in the coastal nearby area then would be replaced by cold water from the deep. The strong existence of coastal upwelling in these locations above can also related to the stronger area of wind speed and local surface current as well as cyclonal vortex position. As analyzed in Figure 9, the strong upwelling in the southern Java sea waters during JJA period occurred simultaneously with the strong negative WSC value, stronger sea surface current, lower SST and deeper mixing layer. Stronger surface current and deeper mixing layer indicated the massive transport of water column in horizontal and vertical respectively.

On the contrary of JJA easterly monsoon, the DJF period where westerly wind blows persistently over Java and surrounding area that is originally from Eurasian continent, driving surface water near coastal area moved toward left side of the wind, so that, the upwelling area would be found in the north of Java Island. The model depicted that the strong upwelling occurred surrounding Madura and north of East Java, although observational satellite data cannot explain so clearly regarding poor resolution due to clouds obstacle. The weak open sea upwelling appeared in southern ocean could be supposed due to surface divergence influenced by cyclonal pattern.

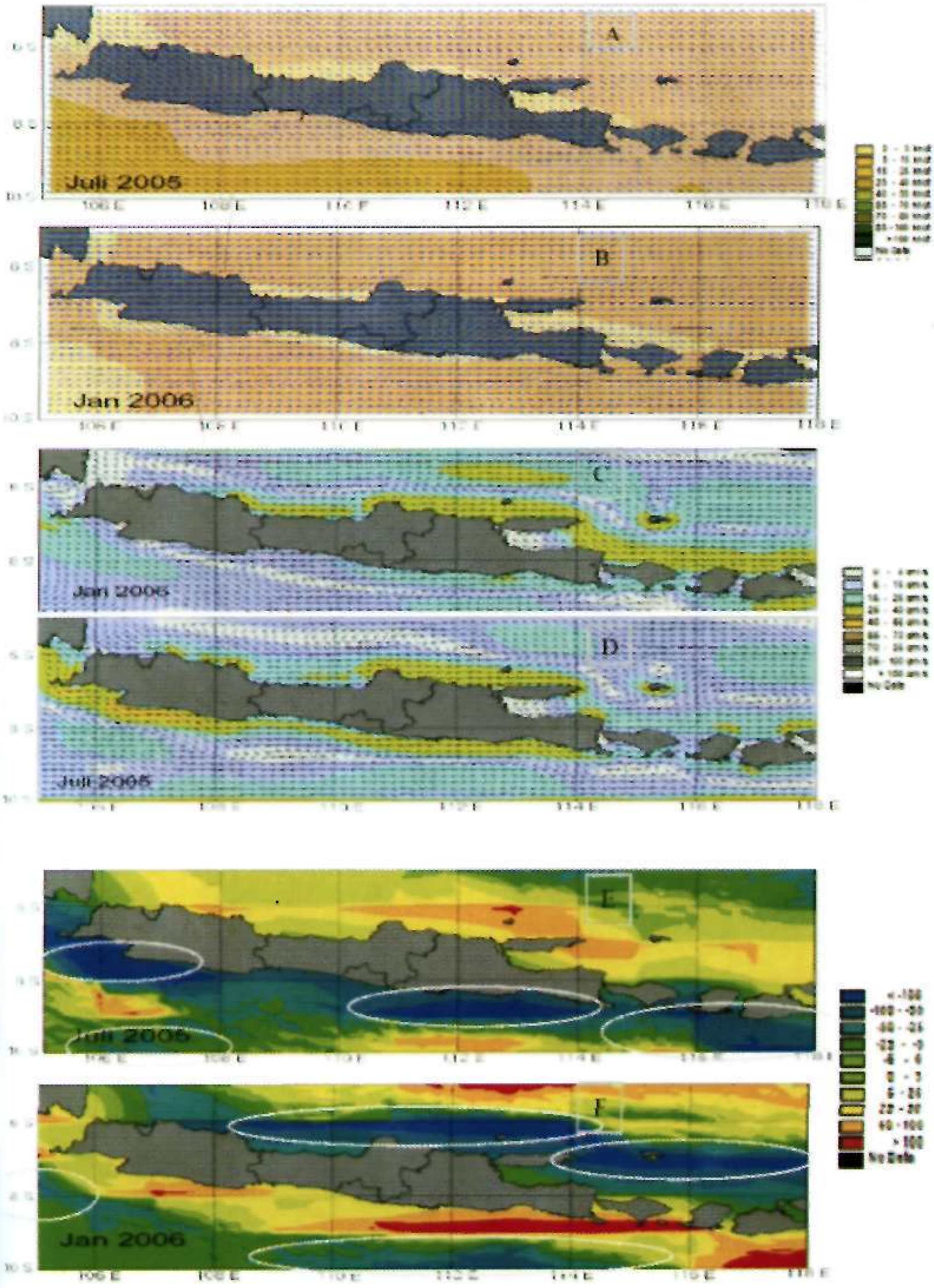

Figure 3. Model outputs of surface wind (A-B), surface current (C-D) and WSC distribution (E-F) in x10-7 dyne.cm'. (blue shade associated to upwelling process and red shade for downwelling).

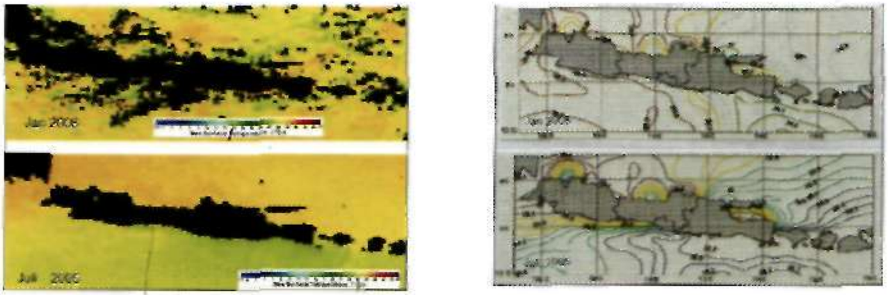

Figure 4. Aqua/Modis images for SST (left panel) and monthly analysis of SST (data: Earth Science Lab Physical Science Division/NOAA) (right panel).

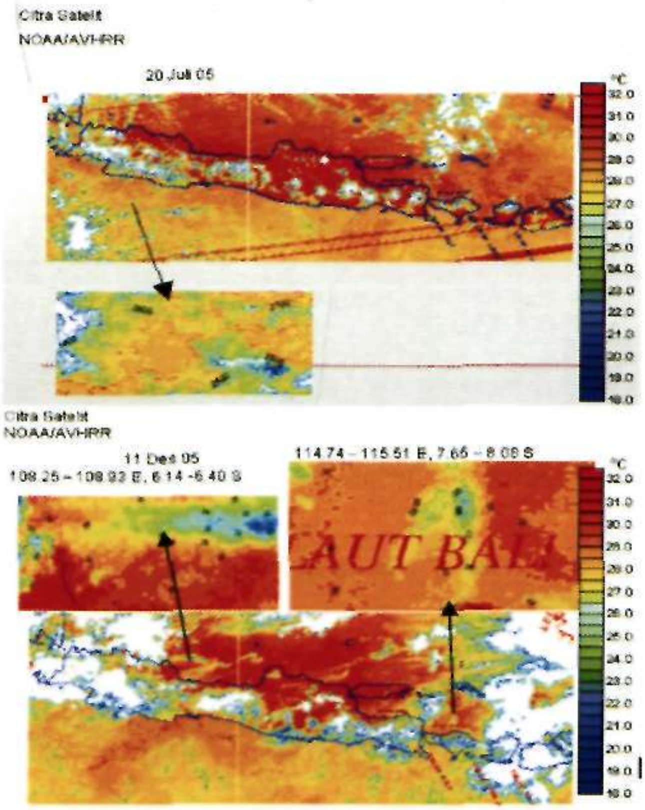

Figure 5. SST Analysis from NOAA/AVHRR for July 20 (above) and Dec 11, 2005 (below).

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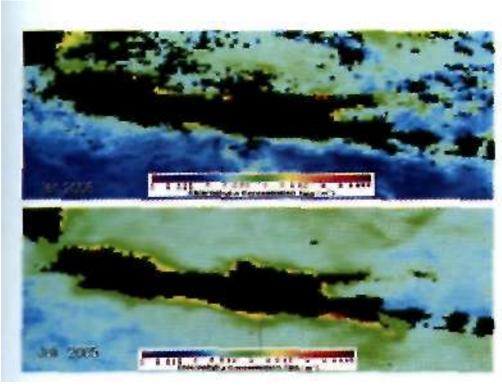

Figure 6. Chlorophyll concentration analysis from Modis/SeaWiFS for January (above) dan July (below).

Each seasonal period that described above showed a response of sea waters to monsoon circulation. Returning monsoon circulation two times a year will characterize and to form seasonal pattern of upwelling/downwelling zone in the surrounding Java-Bali sea waters area.

Thus, periodic upwelling event along coastal area has a fervently relation with seasonal monsoonal wind period which is taking place. Nonetheless, sea response (its current, temperature and upwelling) to atmospheric seasonal motion (wind) is not always simultaneously due to its location and not in uniform in their variability.

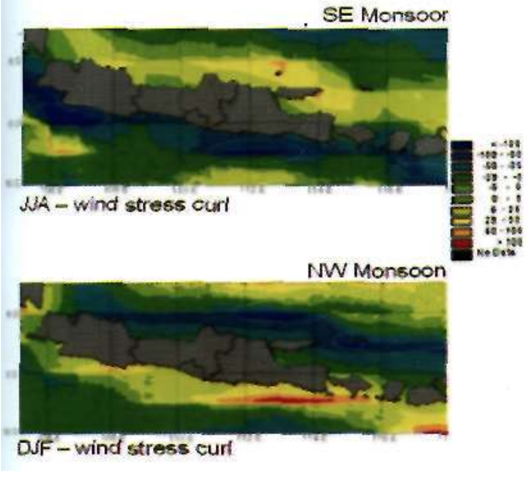

Figure 7. Map of WSC distribution for JJA period (above) and DJF period (below). Circle remarks stronger upwelling zone.

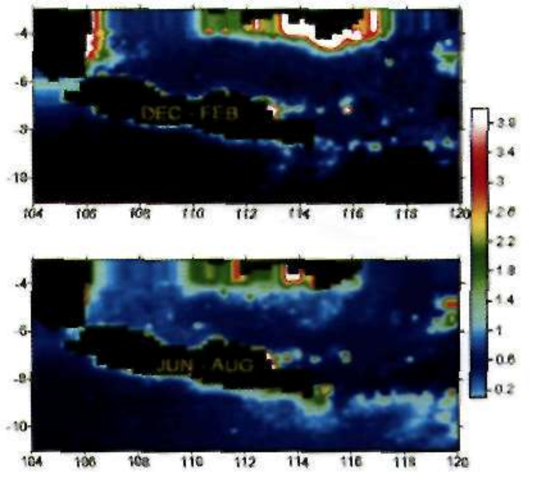

Figure 8. Chlorophyll concentration distribution (mg.m') for DJF period (above) and JJA period (below).

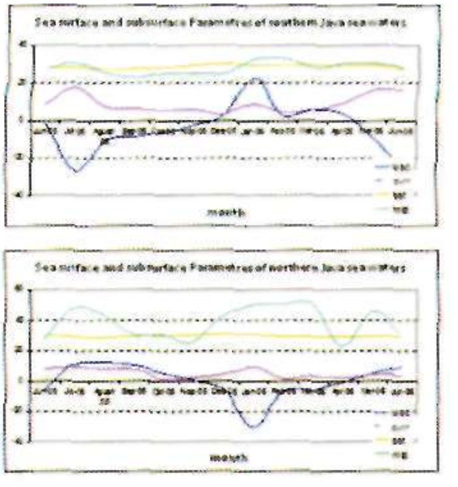

Figure 9. Series of monthly WSC / curl (xlO" dyne.cm"[J]), Surface Current (cm.s[1]), SST ("C) and Mixed Layer Depth (mid, depth in meter) due to Opposite Location around- Domain Interest (Siswanto, 2006).

5. Summary

- From Ekman upwelling model based on negative surface vorticity of WSC has been identified two kind of upwelling: coastal upwelling and open sea upwelling and has classified on the intensity of its curl.

- Coastal upwclling that occurred around Java Island sea waters is intra seasonal type based on the period of occurrence,
- Generally, upwclling appearance over Java-Bali sea waters and surrounding area is as response to monsoon circulation and tight relation to surface movement of the sea and coastal/island morphology.
- Coastal upwelling in the south of Java Island occurred when south east monsoon become active and extended toward north part of the Island, while upwclling in the north Coast of Java Sea occurred during north west monsoon.

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