Analysis of upwelling event in Southern Makassar Strait

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Abstract. The southeast monsoon (SEM) winds which blow in southern Makassar Strait, generate the coastal upwelling phenomenon. The wind data for one year, which is equipped with CTD data from MAJAFLOX cruise results, is used to analyze the phenomenon of upwelling in this region. During the SEM 2015 occurrence, the southeasterly winds speed were in average of 6 m/s, while the highest speed appeared in August and September. Using the Ekman theory's analysis of upwelling during this monsoon period, we could estimate the Ekman transport was about 8.50 m^2/s toward offshore (to the Southwest direction); the upwelled water, occurred from deeper layer, started from the coastal area with vertical velocity was about 6.87 x 10^{-5} m/s – 7.84 x 10^{-5} m/s; and The Ekman layer depth in the upwelling region was approximately 60 m and these were good agreement with CTD observation result.

1. Introduction

Upwelling is an oceanographic phenomenon that involves the rising of water mass at lower temperature which comes from the water column towards the surface layer to replace the surface water mass with higher temperature. This phenomenon will affect the water mass properties distribution; such as temperature, salinity, dissolve or undissolve compounds, and nutrient on the surface water column [1][2][3][4][5][6]. Previous studies have informed that there are some areas in Indonesia's seas that indicate the existance of upwelling phenomena; such as the southern waters of Java [7], the southern waters of the Strait of Makassar [2][4][8][9][10], Banda Sea waters, and the western Water of Sumatra [5].

Southern Makassar strait (SMS) is one of the region which its upwelling occurs annually during southeast monsoon period [2][4][8]. Upwelling phenomenon can be noticed from the decreasing of sea surface temperature (SST) in this region, especially in August – September with the range of temperature between 24 ^{o}C – 30.34 ^{o}C [4][10][11]. It will increase the amount of chlorophill-A in surface layer [1] also the productivity of this region. The number of chlorophill-A in SMS area when southeast monsoon occurs are 0.00 mg/m^3 – 1.144 mg/m^3 [1]. Meanwhile, the concentration of chlorophyll-A during southeast monsoon is in the range of 0.4 mg/m^3 - 0.7 mg/m^3 [12].

Makassar strait is also the main path of the ITF which passes through Indonesian waters. The ITF stream that passes through the Makassar strait is the stream that has followed the pattern of topographic depth. In southern part of the strait of Makassar (SMS region) show tthe distribution of flow. Most of the stream flow into the canal in the west, while some of it flow into the canal in the deeper eastern part. In southeast monsoon circumtances, the flow velocity in the area of SMS on surface layer is affected by the reversal of the direction of the wind [13]. This causes the surface current on this area strengthened this period.

Southeast monsoon winds that blow in the SMS area become the factor that evokes an upwelling. The wind blowing will generate a water mass transport known as Ekman transport. Generally, upwelling phenomenon in coastal area is formed by Ekman dynamic process in the surface layer [14]. The dynamics of the surface layer are due to the influence of the wind that will cause the displacement of water mass that influenced by the direction of Coriolis factor. While transport away from land boundary, according to the theory, there will be a balance from transport that leaves the boundary. This process will induce a lifting on water mass and it is known as upwelling. In the other hand, it will make a downwelling if the water mass is accumulated in land boundary which is caused by surface transport. In general, the dynamic caused by wind blowing in surface layer--will form a transport process known as Ekman transport and Ekman pumping [15].

Utilization of satellite imagery data, such as imagery SST and chlorophyll-A, is commonly occured in studying the phenomenon of upwelling in the SMS region. For complete information on upwelling in this region, the analysis of the Ekman dynamics that occur in the region needs to be done. This study proposes to complement the information about the phenomenon of upwelling by using the Ekman dynamic approach through transport value, Ekman depth, and the condition of the Ekman vertical speed when the occurrance take place.

2. Methods

Temperature data were collected from the field observation in August 2015 conducted by MAJAFLOX cruise. MAJAFLOX Cruise is a research activity conducted by multi institutionl i.e IPB, P3GL, and BPPL. Temperature data were recorded using CTD (Conductivity, Temperature, Depth) SBE V19plus version with 4Hz frequency rate. There were 27 stations fully recorded and these stations were divided into three main; i.e Java sea zone, southern Makassar Strait zone, and Flores Seas zone. This study used observation data station which located in southern Makassar strait (station 17 - station 23) (figure 1a). The data will show in cross section profile. Sea surface temperature (SST) is also provided to support the analysis, especially spatial distribution of surface temperature. This based on spesific time period downloaded from INDESO homepage (http://www.indeso.web.id/indeso_wp/index.php). Spatial resolution of data was about 0.02° x 0.02° from May to october 2015. The data was a composite result from four satellites that carry SST recording sensor. The wind data was downloaded from ECMWF homepage (http://apps.ecmwf.int/dataset/data/interim-full-daily) with spatial resolution 0.125° x 0.125°. Wind U10 component and wind V10 component were used in this studyas well as Wind data from May to october of 2015. The daily average data that were used are from six –hourly data. Both data (SST and Wind data) region are from 4S – 7S and 117E – 121E.

Surface layer dynamic analysis when upwelling occurred in the area of interest, is divided into three calculations. The first one is Ekman transport, the second one is vertical speed and the last one is Ekman depth. Ekman transport calculation is based on wind drag value (τ_n), homogenous water mass density (ρ), and coriolis parameter effect (*f*) [4][16] expressed in equation (1).

$$M_{yE} = -\frac{\tau_x}{\rho f}\,;\, M_{xE} = \frac{\tau_y}{\rho f} \quad (1)$$

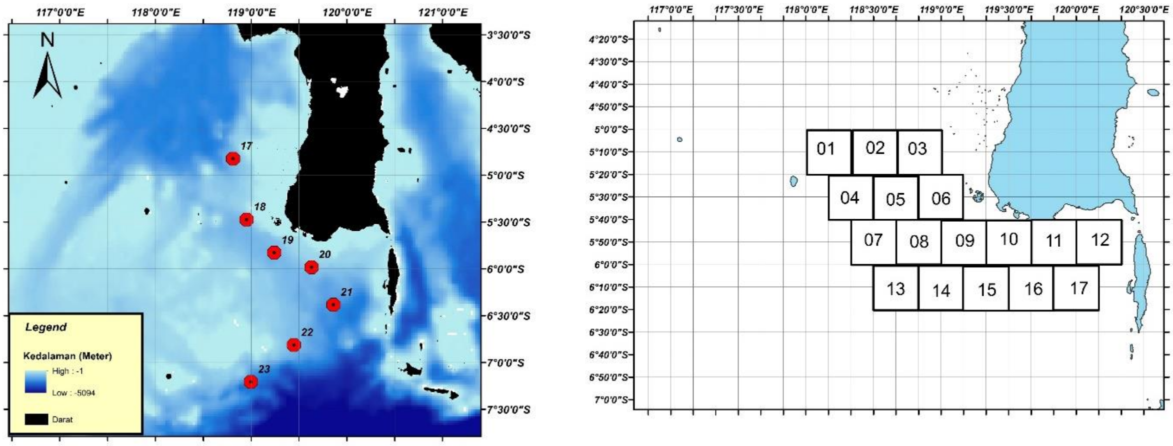
Where M_{yE} is Ekman transport perpendicular coastline (cross shore transport) and M_{xE} is Ekman transport alongshore coastline (alongshore transport). M_{xE} is the value that used to indicate transport magnitude while upwelling occurs. Ekman depth (D_E) indicate the depth below the surface layer which the wind is still influenced by Ekman dynamic. Ekman depth (D_E) can be presented in equation (2).

$$D_E = \frac{4.3\,W}{\sin|\theta|^{\frac{1}{2}}} \quad (2)$$

Where theta (θ) is position of latitude. The vertical speed (w_E) on Ekman layer was calculated by equation (3).

$$-\rho\,\mathrm{w}_E = \frac{\delta M_{xE}}{\delta x} + \frac{\delta M_{yE}}{\delta y} \quad (3)$$

Vertical speed (w_E) indicates convergence (Ekman pumping) that is associated with downwelling if the value are plus and also indicates divergence (Ekman suction) that is associated with upwelling if the value are minus. New grid (1/3° x 1/3°) is used to calculate the number of average vertical speed by using an approach of vertical speed value inside the new grid (figure 1b).



(a) (b)

Figure 1. (a) Station point of CTD Cast in MAJAFLOX Cruise 2015 over SMS area; (b) Area calculation of Ekman transport divided into 17 grid area. Resolution of grid area used 1/3° x 1/3°

Ekman transport estimation that describes the total number of transport average is calculated by integrating the dimension of length (distance) of the area of upwelling region from the distribution of SPL in August 2015. The size of the region of upwelling in question is the extent of the territory which has SST with 26°C isotherm. Determination of isotherms used in determining the area of upwelling is based on the distribution of temperature of the water column that looks raptured during the period of August, 2015 (figure 2).

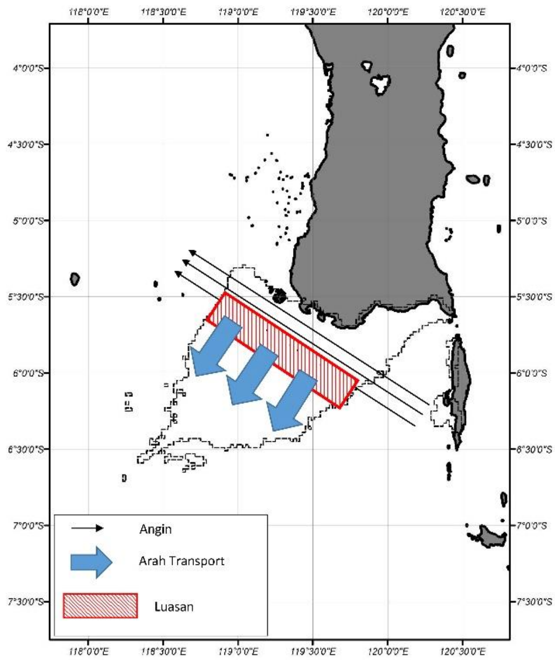
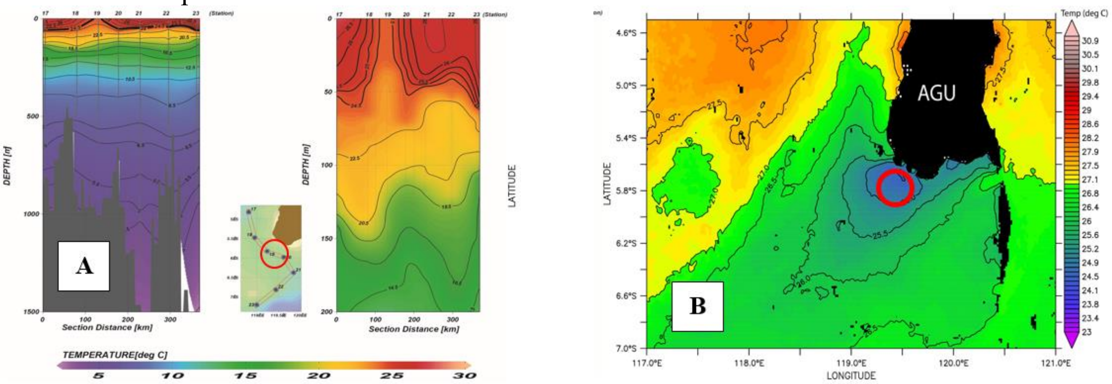


Figure 2. Calculation of transport based on isotherm 26. Integration of transport value along line A-B used to calculate total transport while upwelling occur

3. Results

SST distribution in the southeast monsoon period ranges in temperature between 24.22°C - 30.80°C. SST distribution in the southeast monsoon period from May to October shown the presence of SST low temperature (isotherm 24°C to isotherm 26°C) rather than the SST in the surrounding area. The existence of a low temperature SST looked expanding every month. The formation of the low SST detected came from the south coast of the mainland of southern Sulawesi and was expanding its range consistently until the period of September, which the beginning period was in the month of May.

The lowest surface temperature in May was 25.90°C. It was detected on southern region of Sulawesi (120.03 E, 5.55 S). The average of surface temperature for the entire water in research area was about 28.90°C. The temperature decreased on June up to 25.40°C with average surface was 28.16°C. On July, the surface temperature decreased continuously with minimum temperature was 24.32°C. Average surface temperature was 27.11°C. In August, the lowest surface temperature recorded was 24.43 °C and average of surface temperature was 26.70°C. Decreasing surface temperature still recorded in September. Lowest temperature in September was 24.22 °C with average surface temperature was 26.74°C. Temperature decreas stopped on October. Surface temperature increased 0.89 with average surface temperature was from 24.70°C - 30.26°C. The distribution of low surface temperature at southeast monsoon periode was oriented to southwest side of south Sulawesi.



(a) (b)

Figure 3. (a) Cross section profile of temperature from MAJAFLOX station data (St 17 - St 23); (b) Red circle shows the area of low temperature develop in southeast monsoon periode. This is associated with water mass lifted in station 19 MAJAFLOX.

Cross section profile of temperature data from MAJAFLOX 2015 observation showed the presence of water mass lifting in low SST formation region. This is indicated by the increase of isotherm 24.5 to isotherm 26 toward surface layer (figure 3). Observation of the southern of Makassar Strait began at station 17 and it ended at station 23. The mixed layer of each station ranges from 30 meters to 50 meters below the surface waters with temperatures range from 24.00°C up to 27.50°C at the surface. Mixed layer in this area is strongly influenced by the pattern and strength of the wind that blows in the surface layer. Therefore, on the temperature transversed distribution results from stations 17 to 23, it showed the increase of isotherm 26.00 °C, isotherm 25.50°C, isotherm 25.00°C, and isotherm 24.5°C to the surface. This increase was clearly identified at station 17 to station 21, with the center of the appointment was in the station 19.

In the observation area, Southeast monsoon winds would form the dynamics of the surface layer commonly called Ekman dynamics. Ekman dynamics in the surface layer were composed of the surface Ekman transport and Ekman vertical velocity which could be associated with the occurrence of pumping Ekman (Ekman pumping/downwelling) and the increase of Ekman (Ekman suction/upwelling). For calculating the Ekman dynamics that affected the surface layer, Ekman depth were needed. The Ekman depth distribution in the southeast monsoon period is described as follows.

Southeast monsoon with a faster wind caused the formation of a deeper depth due to Ekman depth which is a function of latitude and wind speed. Areas on the eastern side of the Java Sea with the latitude of 5.4S to 6.4S is the region with the deepest Ekman layer compared to other water areas. Ekman depth in this region has reached 90 meters in depth with a pattern of widespread deployment towards the west side of the Flores Sea. Ekman depth of maximum territorial expansion in the southeast monsoon period continued along with the months and the maximum depth reached in August-September.

In the southern of Makassar Strait, Ekman layer depth in the southeast monsoon season ranged from 39.00 meters to 81.00 meters. In the southeast monsoon period, as well as in western monsoon period, it appeared that Ekman depth decreased as it approaches the mainland (coastal). In the waters near the southern of mainland southern Sulawesi, Ekman depth in this period are at a depth of 42.00 to 72.00 meters below the surface.

As in the period of upweling occurrence in southeast monsoon period, also the indication of the upweling formation region which was located in the waters near the southern mainland of Sulawesi (position 5.5S -5.7S 119.3E-119.6E), Ekman depth conditions in this area varies between a depth of 40.00 meters to 75.00 meters below sea level. This is linear with the detection of the mass removal of water from vertical profiles of temperature (figure 3) which indicates the existence of a mass removal of water from depths ranging from 45 meters to 60 meters to the surface. This information suggested that the existence of upwelling that occurs in the southern Strait of Makassar is caused by the wind which then form a pattern of Ekman transport to the surface waters.

Vertical speed at the observation area was calculated with the new grid area, as described in the method. Vertical speed when the monsoon period in the southeast region of observation is predetermined in the graph below.

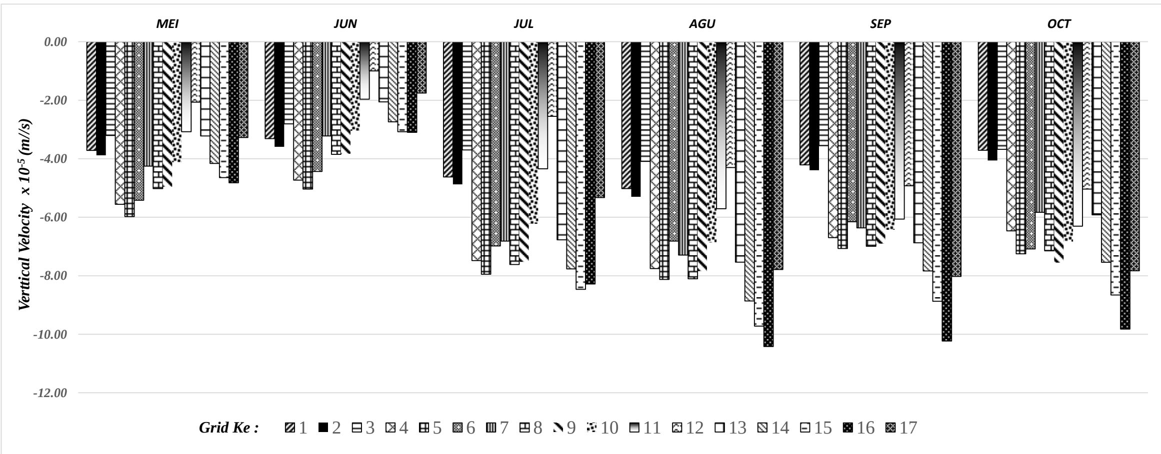


Figure 4. Vertical speed distribution while southeast monsoon. While southeast monsoon period, vertical speed gave negative value. That indicates the Ekman suction wasoCcur on this period. This phenomenon is associated with upwelling

The value of the vertical velocity of the grid element was calculated and shown a negative value. This indicates that during the period of monsoon southeast, the Ekman increase (Ekman suction) which are further associated with upwelling occurred throughout the period. Figure 6 indicates that in August and September, the average Ekman vertical velocity was increased. In May, the average vertical velocity of the Ekman grid observation reached 4.2 x 10^{-5} m/s. In August, the average vertical speed of Ekman was 7.15 x 10^{-5} m/s and it was maximum. Vertical speed of Ekman reached 6.56 x 10^{-5} m/s. In october, Ekman vertical velocity at observation grid average decreased in compare to september period. Ekman vertical velocity in october was at 6.51 x 10^{-5} m/s. On grid 09 (G09) as well as grid 10 (G10) as an area that represents the area of the formation of upwelling based on the distribution of surface temperature (SST) in the period of the monsoon southeast region observations which show the value of vertical speed during periods of maximum incidence of upwelling (august - september) that reached 6.87 x 10^{-5} m/s (G10) and 7.84 x 10^{-5} m/s (G09).

Ekman transport value that crossed coastline south Sulaweasi is the value of transport used in indicating and determining the upwelling region of the periodic monsoon southeast. The results of Ekman transport crosses the observation area in the southeast monsoon period indicates a minus value. This indicates Ekman cross transport to leave the beach during southeast monsoon period.

The distribution of Ekman transport which left shoreline in the area of observation during the southeast monsoon period indicated that the south area of the mainland of southern Sulawesi namely the position 6.4S - 6.6S and 118.0E - 120.0E is a region which has a maximum value of transport (figure 7). The maximum value of transport seem always to be in the region of the difference lies in the intensity of its transport. Intensity patterns of transport shows that during the period May to August, the intensity of transport has increased is continuous where in May, transport maximum detectable reached 8.60 m^3/s, and then continue to grow until the peak period in August the intensity of transport reaches 14.00 m^3/s. Entering the period september, the intensity of the maximum transport decreased slightly. Transport maximum value in this period in the range of 13 m^3/s to 13.5 m^3/s. Entering the month of October, the value of transport again decreased. Transport a maximum of 13 m^3/s with a distribution area that get maximum transport is not covering the previous period.

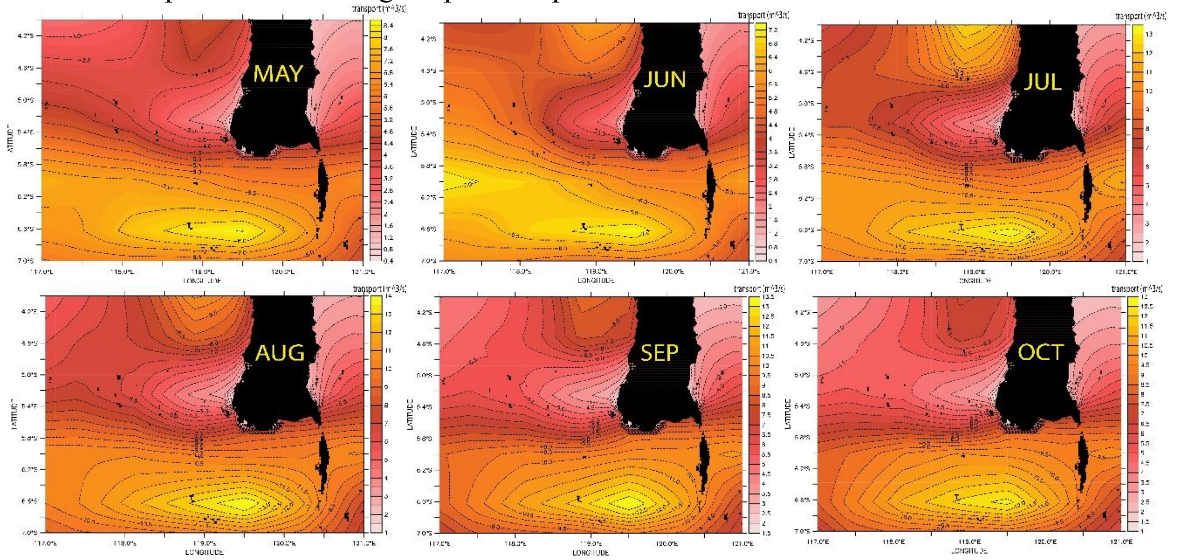


Figure 5. Cross shore transport distribution depart from shoreline. Distribution show on iso transport line contour that flow oriented more southwest.

In areas near the coast of southern Sulawesi which is based on the hue, SST suggest that the region as a region of mass removal of water which is marked by the decline in SST in the region, the transport value generated on the southeast monsoon period showed an increase as a common trait of the study area. The initial period of the southeast monsoon demonstrated in this area of transport ranging from 3.00 m^3/s – 4.50 m^3/s. Then the increas continues until in August the value of the transport reaches 8.50 m^3/s. The direction of movement of transport seemed to south - southwest of mainland southern Sulawesi.

4. Discussion and Conclusion

The SST distribution and vertical distribution conditions of variable temperatures in the period of August 2015 is the culmination of the southeast monsoon conditions in the region of observation, true upwelling events happening in the area. Decrease the temperature with a difference of nearly 3.00 ^oC be a strong indicator the mass removal of water from the water column to the surface. The most influential factor for this incident is the result of southeast monsoon winds that pass over the surface of the observation area thus causing the mass transport of the water leaving the beach.

Ekman depth value is based on the area around the site thought to be the point of appointment of the mass of water (stations 19 MAJAFLOX), Ekman depth value reaches 40 meters to 75 meters below the surface. This corresponds with the results of the cross section profile of temperature from stations 17 to station 23 indicating the mass removal of water from the water column at a depth of around 60 meters. This clearly illustrates that Ekman depth value which is a function of the wind blowing on the surface has a value conformity with the fact the mass removal of water through the results of cross section temperature profile.

Reviewing Ekman vertical velocity value associated with a value that indicates the speed of the moving mass of water column by depth changes due to events mass drownings or removal of the water, on the southeast monsoon period average vertical velocity shows a minus value. Minus value of the vertical velocity calculations indicates a phenomenon appointment Ekman Ekman upwelling is associated with the presence in the area. Ekman vertical velocity value in the region of the alleged establishment of upwelling area is at 6.87 x 10^{-5} m/s to 7.84 x 10^{-5} m/s.

Furthermore, based on transport leaving the beach caused by the Ekman process, transport distribution value indicates a negative value for the entire observation area. This indicates that the average transport that occurs is to keep off from the shore with the amount of different transport between regions. The closer to the land, the smaller transport value given. The total value of transport in the area bounded by isotherm 26 in SST were 175.5 m^3/s with the direction was to keep off the shoreline.

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