Coastal upwelling in Southern Coast of Sumbawa Island, Indonesia

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Abstract. Circulation and water mass characteristics in southern coast of Sumbawa Island is strongly influenced by monsoon which change each season. This research aims to (1) identify the Ekman transport and Ekman pumping variations and (2) analyse the SST and chlorophyll-a variability. During Juni-July-August (JJA) season, the highest value of Ekman transport (-0.72 $m^2 s^{-1}$) moves the water mass towards Indian Ocean while Ekman pumping ($0.15x10^{-4} m^2 s^{-1}$) rises the water mass to the surface (upwelling). Impact of coastal upwelling was identified by cooling SST and high chlorophyll-a. Coolest SST (26.58°C) associated with highest chlorophyll-a (0.6 mg m^{-3}) were found in JJA season. Inter-annual variation of SST and chlorophyll-a concentrations during 2003-2015 is driven by Ekman transport and Ekman pumping. Coolest SST and highest chlorophyll-a were found in JJA season in 2006 with an average value of 25.98°C and 0.78 mg m^{-3}, also in JJA season in 2008 with an average value of 26°C and 0.71 mg m^{-3}. Thus the process of Ekman transport and Ekman pumping has an important role in lifting the cold water high nutriens from the deeper layer to surface. The high concentration of chlorophyll-a in water is the impact of appointment nutrient from the deeper layer by the coastal upwelling.

1. Introduction

Circulation and water mass characteristics in southern coast of Sumbawa Island, located in the northeast of Indian Ocean, are affected by monsoon system resulting in seasonal variability. Non-local phenomena that interact with the system will affect monsoon semi-annual, annual and interannual variability [1][2]. Southern coast of Sumbawa Island has highest wind speed in JJA that is driven by southeast monsoon wind, where the wind move from southeast to northwest [1]. Southeast Monsoon wind caused Ekman transport which is directed away from south coastal of Java and Sumbawa. It cause vacuum in the water mass that result in increasing water mass (upwelling) from the deeper layer toward the surface layer [3][4].

Coastal upwelling is a type of upwelling, which occurred near the coast as a result of Ekman transport and –wind that blows uniformly along the shore which moving the water mass toward or away from the coast. Compensation of the water mass loss in the ocean moves the cooler water with rich of nutrients from the deeper layer to surface. The cooler water that lifted and rich of nutrients stimulates the growth of primary producers such as phytoplankton and fish production. Thus, coastal upwelling has a significant impact on ecosystem and fisheries [5].

Besides Ekman transport, Ekman pumping which driven by the wind convergence or divergence increase local upwelling significantly [6][7][8]. Ekman pumping process moves wind divergence in surface water and lifted the water mass rise to surface. Compared to Ekman transport, Ekman pumping give the same or even greater contribution to the upwelling procces in many regions [7][8][9][10]. Driving factors of coastal upwelling is analyzed through Ekman transport and Ekman pumping values. Meanwhile, the impact of coastal upwelling is analyzed through the distribution of SST and chlorophyll-a concentration in surface water [11].

2. Methodology

2.1. Data

Data used for this research were monthly SST with spatial resolution 0.125° x 0.125° and monthly surface wind with spatial resolution 0.125° x 0.125°. Both dataset are provided by European Centre for Medium-Range Weather Forecasts http://www.ecmwf.int [12]. Monthly chlorophyll-a data with spatial resolution 0.036° x 0.036° is provided by Moderate Resolution Imaging Spectroradiometer (MODIS). Period of SST, wind, and chlorophyll-a data is from January 2003-December 2015 (13 years).

2.2. Methodology

2.2.1. Wind stress

The calculation of wind stress for each component of the wind using the assumption that the x-wind component in the direction parallel to the coast and the y-wind component in the direction of the shore. Calculation of the friction of the wind stress expressed in equation 1 [13] :

$$\tau_x = \rho_U C_D |\vec{v}_H| U_{10} \qquad \tau_y = \rho_U C_D |\vec{v}_H| V_{10} \tag{1}$$

Where :

τ_x = wind stress parallel to the coast (kg m^{-1} s^{-2})
τ_y = wind stress upright to the coast (kg m^{-1} s^{-2})
C_D = drag coefficient = 1.5 x 10^{-3}
ρ_u = air density = 1.3 kg m^{-3}
$|\vec{v}_H|$ = wind magnitude (m s^{-1})
U_{10} = zonal wind component (m s^{-1})
V_{10} = meridional wind component (m s^{-1})

2.2.2. Ekman transport and Ekman pumping Calculation

Ekman transport calculations in parallel and vertical components of the coast can be calculated using wind stress data. In addition, the calculation of Coriolis parameter can used the equation 2 :

$$f = 2\,\Omega \sin \Theta \tag{2}$$

where :

f = coriolis parameter (rad s^{-1})
Ω = rotation velocity = 7.29 x 10^{-5} rad s^{-1}
Θ = latitude

Ekman transport calculation using equation 3 [14] :

$$M_{xE} = \tau_y / \rho_a f \qquad M_{yE} = -\tau_x / \rho_a f \tag{3}$$

where :

M_{xE} = Ekman transport parallel to the coast (m^2 s^{-1})
M_{yE} = Ekman transport upright to the coast (m^2 s^{-1})
τ_x = wind stress parallel to the coast (kg m^{-1} s^{-2})
τ_y = wind stress upright to the coast (kg m^{-1} s^{-2})
ρ_a = water density = 1025 kg m^{-3}
f = coriolis parameter (rad s^{-1})

Ekman pumping calculations using Ekman transport data parallel and vertical components of the coast. Ekman pumping calculation using equation 4 :

$$-\mathbf{W}_{\mathrm{E}}= \frac{\partial \mathbf{M}_{\mathbf{xE}}}{\partial x} + \frac{\partial \mathbf{M}_{\mathbf{yE}}}{\partial y} \tag{4}$$

where :

W_E = Ekman pumping ($m^2\,s^{-1}$)
M_{xE} = Ekman transport parallel to the coast ($m^2\,s^{-1}$)
M_{yE} = Ekman transport upright to the coast ($m^2\,s^{-1}$)

W_E are the Ekman pumping events associated with convergence or divergence of Ekman transport. Positive Ekman pumping ($W_E > 0$) indicates upwelling and negative Ekman pumping ($W_E <0$) indicates downwelling. The calculation of Ekman transport and Ekman pumping were done assess its contribution the coastal upwelling in southern coast of Sumbawa Island.

3. Results and Discussion

3.1. Ekman transport and Ekman pumping Calculation

Surface wind variations can moves the Ekman transport and Ekman pumping in Southern coast of Sumbawa Island (figure 1). Ekman transport dominantly moves the surface water mass to Indian Ocean. Ekman transport process occurs continuously may impacting water column and the pressure gradient along the inshore waters [14]. as a result of the pressure gradient then the water mass will balance, so that the water mass move towards the coast to follow the slope of the seafloor moving towards the surface and move the Ekman pumping process.

December-January-February (DJF) season has an average wind speed 3.19 m s^{-1} and dominantly moving from west to east. March-April-May (MAM) season has an average wind speed 3.19 m s^{-1} and changes in wind direction from southeast to southwest. It caused by the strengthening of the southeast monsoon winds over the water. JJA season has an average wind speed 4.44 m s^{-1} and Southeast monsoon wind strongly occurs in this season. September-October-November (SON) season has decreased in wind speed average from the previous season 3.44 m s^{-1} and changes in wind direction from southeast to the north. It caused by the influence of the southeast monsoon winds that has been decreased. Variations in wind speed and direction monsoon blows in Southern coast of Sumbawa Island will affect the variation of the Ekman transport and Ekman pumping.

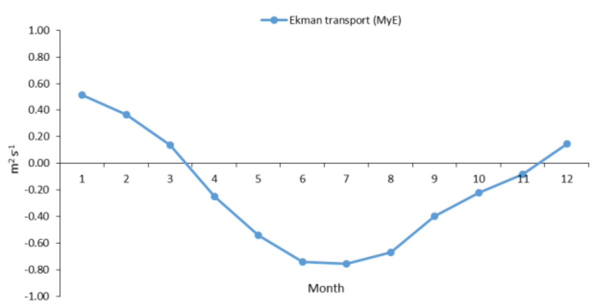

Figure 1. Monthly variation of Ekman transport in southern coast of Sumbawa Island during 2003-2015.

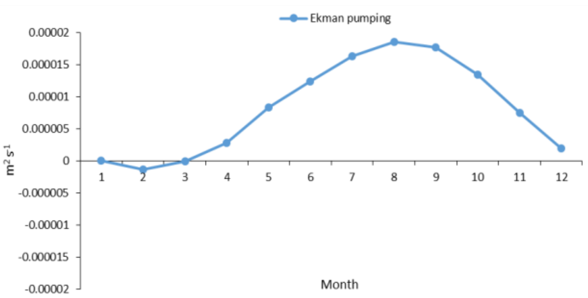

Figure 2. Monthly variation of Ekman pumping in southern coast of Sumbawa Island during 2003-2015.

Value Ekman transport components paralell to the coast (M_{yE}) was calculated using wind stress data component parallel to the coast (τ_x) (figure 1). The calculation is done to see the trend of the mass of water moving toward or away from the coast. Determining the direction Ekman transport leading to the coast is marked with a positive value (+) and towards the open sea is characterized by a negative value (-) [15].

Ekman transport in DJF season has an average value 0.32 $m^2 s^{-1}$ and showed an increasing trend of mass transport volume of water toward the coast. MAM season has an average value of -0.19 $m^2 s^{-1}$ and showed an increasing trend of mass transport volume of water towards the Indian Ocean. JJA season has an average value of -0.72 $m^2 s^{-1}$ and showed an increasing trend of volume water mass transport towards the Indian Ocean. SON season average value of -0.22 $m^2 s^{-1}$ and showed the downward trend in the volume of water mass transport towards the Indian Ocean. Wind stress component parallel to the coast (τ_x) dominantly move the water mass into the Indian Ocean. It proves by the trend of events in MAM, JJA and SON seasons.

Ekman pumping value is calculated using Ekman transport which paralell to the coast component (M_{xE}) and vertical to the coast (M_{yE}) (figure 2). Upwelling and downwelling phenomenon is illustrated by the analysis of vertical transport of water mass in Ekman layer. Positive value (+) indicates the lifting of the water mass (upwelling) and negative (-) indicates the sinking water mass (downwelling).

DJF season has an average value of $0.34x10^{-6}$ $m^2 s^{-1}$ and indicates the lifting of water mass (upwelling). MAM season has an average value $-0.33x10^{-5}$ $m^2 s^{-1}$ and showed a tendency of sinking water mass (downwelling). JJA season has an average value of $0.15x10^{-4}$ $m^2 s^{-1}$ and showed a tendency of lifting of water mass (upwelling). SON season has an average value of $0.12x10^{-4}$ $m^2 s^{-1}$ and showed a tendency of lifting of water masses (upwelling). Ekman transport which paralell to the coast component (M_{xE}) and vertical to the coast (M_{yE}) variations dominantly move the water mass from bottom to surface along the coast. It proves by the trend of events in DJF, JJA and SON seasons.

Process Ekman transport and Ekman pumping values occur JJA season, caused by the influence of the movement of southeast monsoon winds which getting stronger within the season [16]. Ekman transport process has a greater contribution than the Ekman pumping on the incidence of coastal upwelling. It is caused by the loss of water mass on the surface that move towards the Indian Ocean. The loss of water mass will increase the occurrence of coastal upwelling, where there is appointment of water mass with high nutrient abundance from bottom water. Required lag time from appointment of nutrients to found an abundance of chlorophyll-a concentration on the surface of the south ocean of Sumbawa Island.

3.2. SST and Chlorophyll-a Variations

Variation value of Ekman transport and Ekman pumping has an impact on distribution of SST and chlorophyll-a in surface water (figure 3). The average value of SST from DJF to JJA season has decreased and increased in SON season (DJF:29.32°C; MAM:29°C; JJA:26.58°C; SON:27.85°C). Meanwhile, the average value of chlorophyll-a from DJF to JJA season has increased and decreased in SON season (DJF:0.13 mg m^{-3}; MAM:0.22 mg m^{-3}; JJA:0.6 mg m^{-3}; SON:0.37 mg m^{-3}). Another factor affecting the distribution of high concentration of chlorophyll-a in coastal area is nutrient supply which is product of run-off from the mainland and the stirring process from deeper layer (mixing) that intensive along the coast [17].

The strong lifting of water mass mostly found in cooler SST and high chlorophyll-a concentration [18]. The highest incidence of upwelling has SST range 25-26°C and chlorophyll-a range 0.6-0.7 mg m^{-3}. While upwelling occurs when SST range 29-30°C and chlorophyll-a concentration below 0.2 mg m^{-3}. SST distribution is inversely correlated with chlorophyll-a concentration. Lowest SST and highest chlorophyll-a found in JJA season, where the monthly variability, from June to August (JJA) was found the warming SST while chlorophyll-a is increase. Temperature affects the solubility of gases needed for photosynthesis such as CO_2 and O_2. These gases are easily dissolved at a lower temperature than high temperature, resulting in increased photosynthesis rate at a low water temperature.

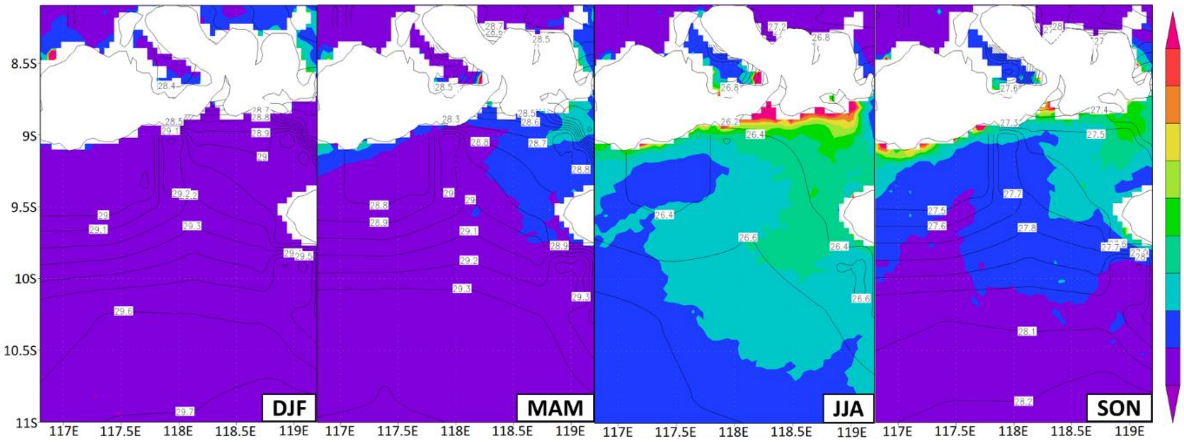

Figure 3. Seasonal variation of SST (contour) and Chlorophyll-a (colour) in southern coast of Sumbawa Island during 2003-2015.

3.3. Inter-annual Variations of Coastal upwelling

Inter-annual variation of Ekman transport and Ekman pumping during 2003-2015 is driven by the monsoon winds (figure 4). Variations in monsoon wind speed and direction will affect the fluctuating value of Ekman transport and Ekman pumping. The maximum value Ekman transport and Ekman pumping occurred in JJA season in 2006 with an average value of -0.85 $m^2 s^{-1}$ and $0.2x10^{-4}$ $m^2 s^{-1}$, also in JJA season in 2008 with an average value of -0.75 $m^2 s^{-1}$ and $0.21x10^{-4}$ $m^2 s^{-1}$.

Inter-annual variation of SST and chlorophyll-a concentrations during 2003-2015 is driven by the Ekman transport and Ekman pumping (figure 5). Coolest SST and highest chlorophyll-a were found in JJA season in 2006 with an average value of 25.98°C and 0.78 mg m^{-3}, also in JJA season in 2008 with an average value of 26°C and 0.71 mg m^{-3}.

Climate variability (ENSO and IOD) may affect the value of SST and chlorophyll-a. Upwelling intensity increases with cooling SST condition and high concentration of chlorophyll-a when IOD(+) and El Nino occur simultaneously in 2006 in the ocean of South Java [18]. Then in 2010, IOD(+) and La Nina occur, where IOD(+) has high impact on SST and chlorophyll-a value in ocean of South Java than La Nina [19].

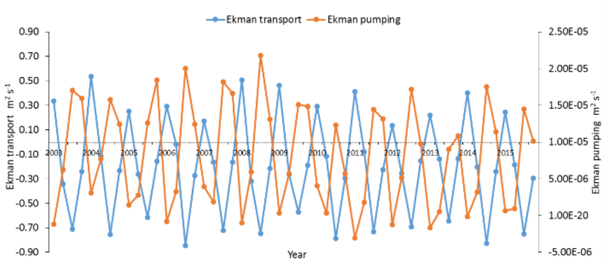

Figure 4. Inter-annual variation of Ekman transport and Ekman pumping in southern coast of Sumbawa Island during 2003-2015.

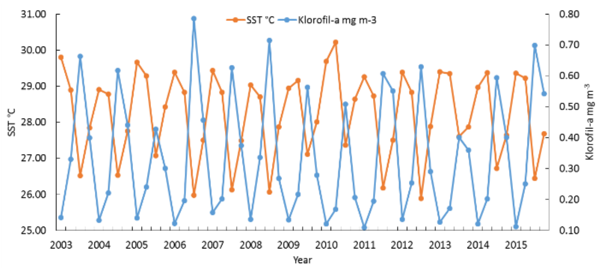

Figure 5. Inter-annual variation of SST and Chlorophyll-a in southern coast of Sumbawa Island during 2003-2015.

4. Conclusion

Coastal upwelling in Southern coast of Sumbawa Island is driven by Ekman transport and Ekman pumping. Ekman transport dominantly moves the water mass towards Indian Ocean and Ekman pumping dominantly lift the water mass from bottom to surface (upwelling). JJA season has the highest value Ekman transport (-0.72 $m^2 s^{-1}$) and Ekman pumping ($0.15x10^{-4}$ $m^2 s^{-1}$). Highest impact of coastal upwelling occurred in JJA season with the coolest SST (26.58°C) and the highest chlorophyll-a concentration (0.6 mg m^{-3}). Thus the process of Ekman transport and Ekman pumping has an important role in lifting the cold water high nutriens from the deeper layer to surface. The high concentration of chlorophyll-a in water is the impact of appointment nutrient from the deeper layer by the coastal upwelling.

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