Influence of coastal upwelling on sea surface temperature trends Banda Sea

H A Rachman1*, J L Gaol1*, F Syamsudin2 and A As-syakur3

1Department of Marine Science and Technology, Faculty of Fisheries and Marine Science, IPB University, Bogor, Indonesia
2Center for Regional Resources Development Technology (PTPSW), Agency for the Assessment and Application of Technology (BPPT). South Tangerang, Indonesia
3Marine Science Department, Faculty of Marine and Fisheries, Udayana University, Bali, Indonesia

*e-mail: jonson_lumbangaol@yahoo.com, herlambangauliarachman@gmail.com

Abstract. The Banda Sea region is one of the locations in Indonesian waters that have high Coastal Upwelling intensity which related to the monsoon pattern. The calculation of Upwelling Index (UI) based on Wind data show that the peak coastal upwelling is from June to September. Analysis of SST trends was carried out in the July-September period based on NOAA OISST data from 1982-2017. The results show that there are differences in the value of SST trends that occur in the Coastal and Oceanic regions. In general, the SST trend in the Banda Sea waters has a positive value (warming) in both the coastal and ocean areas. While the UI trend in coastal and oceanic regions in the Banda Sea tends to decline from the 1982-2017 period. This condition shows that external factors quite influence oceanographic conditions in Banda Sea waters. It is also thought to have caused a decrease in the intensity of the upwelling trend found in the Banda Sea. The results show that the SST trend in the Banda Sea tends to increase during the peak upwelling season (June-September). Meanwhile, the Upwelling intensity trend shows a decreasing pattern which is also confirmed by decreasing trend in chlorophyll concentration.

1. Introduction
Climate Change is one of issue that interested to be studied in recent years. Main role of climate process is the interaction between the ocean and atmosphere. One of key parameters in that process is Sea Surface Temperature. The increase of SST in the last decades due to climate change has been carried out on a regional and global scale [1][2][3]. Especially for coastal region, about 71 % of total region had a significant of warming SST [2]. In recent years, many research about related of coastal warming and intensity of coastal Upwelling [4][5][6][7]. In general, the SST change trend will have a pattern inversely proportional to the coastal upwelling trend. However, in several studies, not all coastal upwelling will experience this condition, due to the influence of local and regional oceanography such as the South Java Waters [5] and the Yucatan Peninsula [8]. One of the waters in Indonesia which has complex regional oceanographic conditions is the Banda Sea.

The Indonesian Maritime Continent is the unique regional location because locate in the tropical region and influenced by global and regional ocean circulation. The main mode of variability in Indonesian Region is the monsoonal cycle of winds are develop during December to February (Northwest Monsoon) and June to September (Southeast Monsoon). One of the location that high influence by Monsoonal wind is Banda Sea that located in Eastern Part of Indonesian region. Banda Sea
is the location that high productivity of pelagic fisheries in Indonesia. The high productivity in Banda Sea mostly influenced by Upwelling Process that impact on high concentration of chlorophyll-a [9, 10, 11]. An increase in the concentration of chlorophyll-a is one indicator in the level of productivity of fisheries contained in these waters [12]. Banda Sea waters are one of the areas with high fisheries productivity in Indonesia [13]. In this research, an analysis of the effect of coastal upwelling on SST change trends and its implications for chlorophyll-a concentrations.

The aims of this paper is to understand spatial and temporal pattern of trend SST and their impact to Upwelling variability in Banda Sea Region. In many location, the implication of global warming have different impact both increase of decrease because of the dynamical oceanography in the region. This study are focus on the used of Satellite Imagery data to analysis of trend Sea Surface Temperature and Chlorophyll-a concentration, and wind datasets from meteorological modelling of analysis the Upwelling Indices. This research can be used as a basis in seeing the impact of climate change on the productivity of waters, especially those in the Banda Sea.

2. Data and method

2.1. Study area

This research was conducted from May to September 2019 in Geographic Information System Laboratory, Department of Marine Science and Technology, IPB University. The study location is in Banda Sea (Fig 1) at Eastern Part of Indonesian Sea Region.

Figure 1. The location of study in Banda Sea region. Dashes (Solid) line means coastal (offshore) location.

2.2. Data

The calculation of SST trend was conducted by daily data from Optimum Interpolation Sea Surface Temperature (OISST) ¼ from Advanced Very High Resolution Radiometer (AVHRR) sensor with spatial resolution 0.25 x 0.25 degree. Data were calculated by satellite SST and assimilation from buoy and ship to make regular database. In this research we use 36 years data of SST from 1982 to 2018. In the process for calculate trend, the data will be averaging from daily to monthly and calculate the monthly anomaly.

Upwelling intensity were calculated based on wind dataset from European Centre for Medium Range Weather Forecast (ECMWF) in ERA-Interim project. Daily data of wind dataset was used in this study with spatial resolution 0.25 x 0.25 degree. The data will calculate to monthly average before calculate
Upwelling Index. To confirm the upwelling phenomena was occurred in Banda Sea, we use chlorophyll-a data from MODIS sensor from 1998 to 2018.

2.3. Data analysis

2.3.1. Upwelling intensity. Upwelling intensity was calculated from Upwelling Index (UI) where calculated from Ekman transport (Q) and Windstress (τ) where x(y) define zonal (meridional) component. The equation to calculate windstress was follow as :

\[
\tau_y = \rho_a C_d (W^2_x + W^2_y)^{1/2} W_y \quad \text{and} \quad \tau_x = \rho_a C_d (W^2_x + W^2_y)^{1/2} W_x
\]

(1)

Where \( \tau \) is wind speed component data where x is zonal and y is meridional, \( \rho_a \) is the air density (1.22 kg m\(^{-3}\)), \( C_d \) is the dimensionless drag coefficient (1.4 x 10\(^{-3}\)). Next, we calculate the Ekman transport (Q) based on windstress calculation :

\[
Q_x = \frac{\tau_y}{\rho_w f} \quad \text{and} \quad Q_y = -\frac{\tau_x}{\rho_w f}
\]

(2)

\( \rho_w \) is the water density (1025 kg m\(^{-3}\)), and \( f \) is the Coriolis force defined as \( f = 2\Omega \sin(\theta) \) where \( \Omega \) is the angular velocity, and \( \theta \) is the latitude of the location in degree. UI is define as Ekman Transport component in the direction perpendicular to the shoreline :

\[
UI = -\sin\left(\varphi - \frac{\pi}{2}\right) Q_x + \cos\left(\varphi - \frac{\pi}{2}\right) Q_y
\]

(3)

Where \( \varphi \) is angle between shoreline and equator line. Range of the angle in this study is from 240 to 270 degrees. Positive (Negative) values correspond to the upwelling (downwelling) favourable condition.

2.3.2. Trend analysis. Trend analysis was calculated from monthly anomaly from every datasets as a slope of linear regression. Anomalies was explaining the difference value between every datasets average of all the time with current period. Trends were calculated at each pixel on SST and Ekman Transport as spatial pattern. The equation of linear model of regression given by :

\[
Y_t = B_0 + B_1 t + e
\]

(4)

Where the \( Y_t \) is value of Y data at t time, \( B_1 \) is the regression coefficient or slope, and \( e \) is the error. The result was describing the tendency of increasing data (positive) and decreasing (negative).

3. Result

3.1. Annual cycle of upwelling indices

Indication of Upwelling indices in Banda Sea was describing by Ekman Transport alongshore (zonal) and perpendicular (meridional) component. Ekman Transport was calculated by monthly ECMWF datasets from 1982-2017 (Figure 2). The pattern of annual cycle of Ekman Transport show during June to September is peak of Upwelling. The negative (positive) value of Ekman transport explaining the direction of vector the Ekman Transport. In Zonal component negative (positive) value show Ekman from east (west) and Meridional explain current from north (south). During June to September, the direction of Zonal Ekman Transport east to west and away from eastern coast (Papua Island) with strength around 2000 to 3000 m s\(^{-1}\) km\(^{-1}\). While in the meridional component show the direction mostly from north to south and away from Banda and Seram Island in Southern Part of Banda Sea. The Strength of Meridional Ekman Transport is around 3000 to 4500 m s\(^{-1}\) km\(^{-1}\). These conditions may be as sign of Coastal Upwelling was occured in Banda Sea during this period. To confirm upwelling phenomenon,
the annual cycle of chlorophyll-a show the same pattern with Ekman Transport where peak in June to September.

![Figure 2. Annual cycle of ekman transport (zonal and meridional) in Banda Sea.](image)

One indication of the Upwelling phenomenon is the increased concentration of nutrients that will affect the chlorophyll-a concentration. Based on the analysis using the monthly SeaWiFS and Aqua Modis data from 1998-2018, show the monthly variation of chlorophyll-a in Banda Sea. In general, chlorophyll-a concentration appears to be higher in the June-November (Southeast Monsoon) period than December to May (Northwest Monsoon). This period is related with monsoonal wind direction which have changed in every six months. It is known that during the June-September period it was the time of the blowing of monsoon winds that was identical to the Upwelling phenomenon in the Banda Sea. Based on Figure 2, it can be seen that during Southeast Monsoon (SEM) period the peak of upwelling in the Banda Sea with a maximum in July-August. Confirmation of the Upwelling incident also revealed that the maximum concentration of chlorophyll-a also occurred during the July and August periods.

![Figure 3. Annual cycle of chl-a concentration in Banda Sea.](image)

3.2. Trend analysis
Based on the results of the monthly data variations for Ekman Transport and Chlorophyll-a found in the Banda Sea, the maximum peak of the Upwelling event was during the June-September period. Where during that period was the Southeast Monsoon winds. Based on this, SST trend analysis will be calculated at the peak of Upwelling (June-September) condition, and the same will be done with Ekman Transport data.
3.2.1. **SST trend.** Monthly SST trend are calculated based on daily data from 1982-2018 on each month of the upwelling peak from June to September (Fig 4). The results show that the Banda Sea area during the period experienced an increase in SST ranging from 0.1 to 0.4°C/dec. Spatially shows the trend of SST in the Banda Sea in the middle and south tends to be higher compared to the northern region. These differences are consistent both from the June to September period. During June, the SST increase was quite high in the northeast region of the Banda Sea. Generally, a significant increase in SST occurred in the northeast area of the Banda Sea (near the coast of Papua Island) in the June-July period with a trend of 0.4°C/dec. As for the central and southern regions, the SST is around 0.25°C/dec. At the peak of the upwelling season period in August and September showed lower SST trends than June-July ranging from 0.15 to 0.23°C/dec. The condition of the lower SST trend is presumably due to the Upwelling phenomenon that occurred in that period.

One indication of Upwelling's occurrence is the strength of Ekman Transport, which is the current due to the wind being aligned and perpendicular to the coastline (Zonal and Meridional components). On the zonal component, there is a trend of a positive trend in the northern part of the Banda Sea (Near the coast of Seram Island and Banda) and negative in the middle and south. Positive trends in the zonal component may indicate a decrease in upwelling strength where the tendency of Ekman Transport direction is closer to the coast. The opposite of the negative trend is the increase in upwelling intensity. During the June and July periods, positive trends occurred in the northern regions around Banda Island and Pula Seram ranging from 0 to 150 m³s⁻¹km⁻¹dec⁻¹. Then in August and September, Negative trend

---

**Figure 4.** Trend SST in Banda Sea during upwelling season.
tendencies weakened in the South Banda region and shifted towards the East. While in the north, it tends to decline and tend to be a Negative trend.

![Figure 5. Trend of zonal ekman transport at Banda Sea during upwelling season.](image)

Next is the meridional component of Ekman Transport, which indicates the direction of the current perpendicular to the coastline moving from north to south. The Ekman Transport Meridional trend pattern was found to vary quite positively and negatively during the peak period of the Upwelling phenomenon. Negative trends can mean that the Ekman Transport pattern is associated with an increase in upwelling intensity, while positive. Generally, from June to September, the Ekman Transport Meridional Trend experienced a Positive Tendency, particularly in areas near the northern coast. The decline in upwelling trends in the northernmost regions occurred in June even reaching 50-100 m$^3$s$^{-1}$km$^{-1}$dec$^{-1}$. Whereas in July, maximum upwelling decreases in the north area and tends to see an increase in upwelling in the middle to southern Banda Sea of 50-250 m$^3$s$^{-1}$km$^{-1}$dec$^{-1}$. Meanwhile, for August and September, positive trends were found in the southern and central parts of the Banda Sea. This indicates a trend of decreasing upwelling intensity in the region.
Figure 6. Trend meridional ekman transport in Banda Sea.

Figure 7 shows the fluctuations of the average monthly SST anomaly over the Banda Sea waters during the upwelling period from 1982–2018. The variations in the data are based on the average SST Anomaly values in June-September. These values are extracted at locations close to the Coast and in the middle of the Banda Basin location (fig 1). The data show that the average SST increase in the Banda at the upwelling peaks near the Coast with Offshore tends to be insignificant at 0.249 and 0.286°C/decade, respectively. The negligible differences in coastal and offshore regions confirm the results spatially in Figure 4.

Figure 7. Average SST anomaly in Banda Sea during June-September 1982-2017. Red and blue line means coastal (offshore) location.
As one of the key parameters found in Waters, the increase in SST will certainly have an impact on other phenomena. Some previous studies mentioned that there is a relationship between increased SST and coastal Upwelling intensity. Spatially Ekman Transport in the Banda Sea Area is experiencing a declining pattern of Upwelling Intensity. The results of the Upwelling Index (UI) analysis during the June-September period showed a pattern of decline in the upwelling intensity (Figure 7). Decreases in upwelling intensity occur at locations near the coast or offshore. Generally, there is an increase in Ekman Transport trends found in the Banda Sea region, whether near coastal or offshore. To find the indication of upwelling, then it will be calculated the value of the coast upwelling based on the equation 3. The analysis shows that offshore or offshore areas, the intensity of the upwelling decrease in average data from June-September. In the area near the coast, the decline of the Upwelling Index was -0.025 m$^3$s$^{-1}$dec$^{-1}$, while the offshore was -0.337 m$^3$s$^{-1}$dec$^{-1}$.

**Figure 8.** Average UI in Banda Sea during June-September from 1982-2018. Red and blue line means coastal (offshore) location.

Chlorophyll is an indicator of the upwelling of a region. There is an indication of the trend of SST and Upwelling will certainly affect the tendency of chlorophyll concentration. Analysis results based on SeaWiFS and Modified Aqua monthly data during the upwelling peak showed that the chlorophyll-a trend in the Border during the period 1998–2019 experienced a decline of -0.02 mg m$^{-3}$dec$^{-1}$ (figure 7). The decrease in the chlorophyll trend may be indicative of a reduction in upwelling in the Banda Sea.

**Figure 9.** Average chlorophyll-a during June-September from 1998-2019.
4. Discussion

The annual cycle results from both Ekman Transport show negative values in the SEM period, and tend to be positive at the time of the Northwest Monsoon (NWM). These positive (negative) values represent directions from Ekman Transport. In the case of the Banda Sea, negative directions for both the Zonal and Meridional components may be offshore. The pattern of Ekman currents away from the coast will result in an increase in the mass of water from the depths to the surface. Result analysis from temporal distribution of Ekman Transport and chlorophyll-a showed upwelling phenomena in Banda Sea occur during Southeast Monsoon (SEM) that peak in June – September.

Increased SST in coastal area has been identified [6, 14, 15]. In that research showed that there are relationship between increased SST trends with Ekman Transport when upwelling happened. Then SST trend will be calculated with linear regression equation using dataset from 1982 – 2018. On this period, generally average SST in Banda Sea was increased 0.28°C per decade. Increased SST tendency to be high then global average almost 0.18°C/dec⁻¹ [16]. Based on the results of the analysis shows the trend of SST that occurred in the Aug-Sep period tends to be lower than the Jun-Jul period. This condition is thought to be due to the influence of the phenomenon of coastal upwelling whose peak occurred in the Aug-Sep period (Figures 1 and 2). This is also consistent with several previous studies which mentioned that the strength of coastal upwelling has a relationship with the SST trend. [4] [5] [14] [15] [17].

The results of the SST trend indicate that the northern region compared to the southern part of the Northern Territory that passes through the Halmahera Sea and the Seram Sea are currents originating from the South Pacific Ocean region [18]. The high level of SST trend found in the north is due to the impact of currents originating from the Pacific Ocean. It is known that SST trends in the Western Pacific region tend to be higher than in other areas[19]. Furthermore, the weakening of the SST trend in the central to southern regions is thought to be due to dynamic conditions in the Banda Sea, one of which is coastal upwelling. To see other influences, a more in-depth study needs to be done, especially the dynamic conditions found in the subsurface of the Banda Sea.

Based on the description in the results section, it has been explained that a decrease in upwelling intensity can indicate the decreasing strength of Ekman Transport, both zonal and meridional trends. Based on the theory that the relationship between SST trends and coastal upwelling is inversely proportional. In general, the Banda Sea can be seen that the SST trend in the Banda Sea as a whole has an upward trend that is either offshore or close to the coast. Meanwhile, the results of the Upwelling Index (UI) calculation show that the UI trend in the Banda Sea region tends to decrease. The decrease can confirm the decrease in UI trend in chlorophyll-a concentration based on satellite imagery data.

5. Conclusion

The Banda Sea is an area with a quite high upwelling intensity which is influenced by the monsoon cycle, which peak occurs in June-September. Most of the Banda Sea region has a trend of increasing SST in the peak upwelling period. The analysis shows that at that time, the Ekman Transport trend tended to show a pattern of decreasing the intensity of Upwelling, especially in the near coastline on Seram and Buru Islands. The decrease in the strength of the Upwelling was confirmed by the calculation of the Ekman Transport to be the Upwelling Index (UI), where the UI value experienced a downward trend both in areas near the coast or offshore. The decrease pattern of UI make the trend SST in Banda Sea mostly have positive trend of SST. To see the impact of the decline, an analysis of the chlorophyll-a trend found in the Banda Sea also shows a downward trend.

Reference

[1] Casey K S and Cornillon P 2001 Global and Regional Sea Surface Temperature Trends J. Clim. 14 3801–3818
[2] Lima F P and Wethey D S 2012 Three decades of high-resolution coastal sea surface temperatures reveal more than warming Nat. Commun. 3 1–13
[3] Levitus S Antonov J and Boyer T 2005 Warming of the world ocean, 1955-2003 Geophys. Res. Lett. 32(2) 1–4
[4] Santos F Gomez-Gosteira M R.Varela Ruiz-Ochoa M and Dias J M 2016 Influence of Upwelling on SST trends in La Guajira system Journal Geophys. Res. Ocean 121(4) 2469–2480
[5] Varela R Santos F Gómez-Gesteira M Álvarez I Costoya X and Dias JM 2016 Influence of coastal upwelling on SST trends along the South Coast of Java PLoS One 11(9) 1–14
[6] Goela P C Cordeiro C Danchenko S Icely J Cristina S and Newton A 2016 Time series analysis of data for sea surface temperature and upwelling components from the southwest coast of Portugal J. Mar. Syst. 163 12–22
[7] Bakun A, 1990 Global Climate Change and Intensification of Coastal Ocean Upwelling Science 247 198–201
[8] Varela R Costoya X Enriquez C Santos F and Gómez-Gesteira M 2018 Differences in coastal and oceanic SST trends north of Yucatan Peninsula J. Mar. Syst. 182 46–55
[9] Gieskes W W C Kraay G W Nontji A Setiapermana D and Sutomo 1990 Monsoonal Differences in Primary Production in The Eastern Banda Sea (Indonesia) Netherlands J. Sea Res. 25(4) 473–483
[10] Susanto R D Moore T S and Marra J 2006 Ocean color variability in the Indonesian Seas during the SeaWiFS era Geochimie Geophys. Geosystems 7(5) 1–16
[11] Moore T S Marra J and Alkatari A 2003 Response of the Banda Sea to the southeast monsoon Mar. Ecol. Prog. Ser. 261(1997) 41–49
[12] Ward T M et al., 2017 Pelagic ecology of a northern boundary current system: effects of upwelling on the production and distribution of sardine (Sardinops sagax), anchovy (Engraulis australis) and southern bluefin tuna (Thunnus maccocyti) in the Great Australian Bight Fish. Oceanogr. 15(3)191–207
[13] Wijaya A Priyono B and Mahdalena N C 2018 Karakteristik Spasial Temporal Kondisi Oseanografi Laut Banda dan Hubunganya Dengan Potensi Sumberdaa Perikanan J. Fish. Mar. Res. 2 75–85
[14] Varela R Álvarez I and Santos F 2015 Has upwelling strengthened along worldwide coasts over 1982-2010? Nat. Publ. Gr. 1–15
[15] Santos F DeCastro M Gómez-Gesteira M and Álvarez I 2012 Differences in coastal and oceanic SST warming rates along the Canary upwelling ecosystem from 1982 to 2010 Cont. Shelf Res. 47 1–6
[16] Good S A Corlett G K Remedios J J Noyes E J and Llewellyn-Jones D T 2007 The Global Trend in Sea Surface Temperature from 20 Years of Advanced Very High Resolution Radiometer Data Journal Clim. 20 1255–1264
[17] Santos F Gomez-Gesteira M deCastro M and Alvarez I 2012 Differences in coastal and oceanic SST trends due to the strengthening of coastal upwelling along the Benguela current system Cont. Shelf Res. 34 79–86
[18] Gordon A L 2005 Oceanography of the Indonesian Seas and Their Throughflow Oceanography 18(4) 14–27
[19] Heureux M L L and Collins D C 2013 Linear trends in sea surface temperature of the tropical Pacific Ocean and implications for the El Nino-Southern Oscillation Clim. Dyn. 40(5–6) 1223–1236

Acknowledgments
We gratefully acknowledge the data received from this organization: Wind Datasets from European Centre for Medium Range Weather Forecast (ECMWF); SST from Optimum Interpolation Sea Surface Temperature (OISST) ¼ from National Oceanic and Atmospheric Administration (NOAA) homepage; and Chlorophyll-a data from Moderate Resolution Imaging Spectroradiometer (MODIS).