Response of upwelling variability to the local and remote forcing in the Banda Sea

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Abstract. The Banda Sea experiences a strong upwelling between April and November associated with the seasonal strengthening of the trade winds. Data of surface wind, sea surface temperature (SST) and salinity in the period of 1990-2008 were used to further study the response of upwelling to the local and remote forcing in the Banda Sea. A local forcing (Ekman Pumping) during Southeast Monsoon plays role in contributing the upwelling intensity indicated by shallower thermocline and colder SST. In addition, this study exhibits that the upwelling strength is controlled remotely by El Niño Southern Oscillation (ENSO) where during El Niño (La Niña) periods in Southeast Monsoon, the upwelling weakens (strengthens) in the Banda Sea.

1. Introduction

Indonesian waters are not only influenced by local factors such as monsoon winds but also by inter-annual global phenomena such as the El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole Mode (IODM). The depth of the thermocline layer which is one indicator of the occurrence of upwelling and downwelling in the waters is influenced by these global and local scale factors. Upwelling and downwelling plays a role in the distribution of nutrients in the water. The thermocline depth has a strong and significant correlation to sea level [1, 2, 3]. Changes in the depth of the thermocline layer correlate with sea level height anomalies, so that the value can be used as an indicator of the occurrence of El Niño and La Niña [2].

Local scale factors such as monsoon winds result in Ekman transport which allows for upwelling or downwelling to be existed. During Southeast monsoon, winds move from the Australian Continent caused a vacuum of surface water in eastern Indonesian waters and large-scale upwelling phenomena were observed in the Banda Sea and in some areas of Indonesian waters [4]. The Banda Sea is in the eastern part of Indonesia (Figure 1) and it is an area affected by monsoon winds and ENSO phenomena. Moreover, Banda Sea is a rich sea in marine resources in the form of diverse types of coral and high levels of primary productivity [5] in [6]. Thus, Banda Sea is area favored by fish, reptiles and marine mammals. Gordon and Susanto (2001)[7] discussed that the Banda Sea surface temperature variability is related to the depth of the thermocline layer which varies seasonally and interannual.

Monsoon winds affect seasonal variations of waters stratification in the Banda Sea [7]. Monsoon winds that move across the Indonesian region cause the Banda Sea to have a type of alternating
upwelling characterized by upwelling in one season and downwelling that occurs in another season. Studies of thermocline layer depth and the strength of upwelling are useful in determining the duration of upwelling, the peak of upwelling, and the area with the highest nutrient. Knowing the location and period of the occurrence of the upwelling may useful to explore the biological resources of the Banda Sea.

![Figure 1. Review area (marked in red) (Map Source: [8])](image)

In this study, seasonal variations of the upwelling in the Banda Sea were assessed using monthly Ekman pumping values calculated based on wind stress curl. In addition, the inter-annual variation on the thermocline layer depth and the strength of upwelling in the Banda Sea were also investigated to determine the effect of remote forcing factors such as the ENSO on the characteristics of upwelling in the Banda Sea. The aim of this study is to study the effect of local and non-local factors, seasonal variations, and inter-annual on the upwelling intensity in the Banda Sea using monthly average wind data, vertical velocity of the model, temperature, salinity, and Ocean Niño Index (ONI). Furthermore,

2. Materials and Method

2.1. Study sites
The Banda Sea is located in eastern Indonesia at a coordinate of 3°S – 9°S and 125°E -133°E with a total area of 584,000 km² [6]. It has a primary and secondary basin [1] in [6]. These basins (indicated by the oval circle in Figure 2) are:
1. North Banda Basin (black oval circle).
2. South Banda Basin (red oval circle).
3. Weber deep (brown oval circle).
4. Basin Flores (yellow oval circle).
The Banda Sea has a varied bathymetric configuration and deeper sea up to more than 7000 m in Weber deep [6]. Seasonal variations caused by the monsoon affect the current system in the Banda Sea [6, 9] in the form of water mass transport from or to the Banda Sea. In this study, nine stations were selected (Figure 2), each represents the western part of Banda Sea (Station 1, 2, and 3), center (Station 4, 5, and 6), and eastern part of Banda Sea (Station 7, 8, and 9).

2.2 Data
The data used in this study are data on temperature, salinity, surface wind speed, and ONI with a time span from January 1990 to December 2008 (19 years) as follows:

• Seawater temperature and salinity data from the simulation model of SODA assimilation:
  Data on sea water temperature and salinity are downloaded and available from the surface to 5375 m depth with data intervals of 10 m near the surface (up to 57 m) and varies between 20 - 200 m. To obtain a vertical profile of temperature, available data at a certain depth were interpolated using the spline cubic method.

• ONI data
  To see the variability of ENSO, the data used as a reference is the ONI data published by NCEP and NOAA (National Oceanic and Atmospheric Administration). The El Niño event is indicated by the value of ONI > 0.5, and La Niña by ONI value < -0.5, while the normal conditions has the ONI value between -0.5 to 0.5.

Figure 2. Position of the station (1-9) in the Banda Sea. (Map Source: GEBCO [8])
• Surface wind speed data in the form of zonal and meridional components
Surface wind speed data from NCEP / NCAR reanalysis monthly is used to calculate the value of surface wind stress. The value of surface wind stress is needed to calculate wind stress curl which is useful for determining the value of Ekman pumping.

2.3. Data processing
Data processing is carried out includes the steps as follows:
1. Determination of the thermocline layer depth.
2. Calculating the Ekman pumping value.
3. Wind and SST distribution.
4. Seasonal and inter-annual variations of thermocline layer depth and the intensity of upwelling.

2.4. Determination of the depth of the thermocline layer
The main data used in determining the thermocline layer depth is temperature data for Station 1 - Station 9. Variability in the thermocline layer depth is expressed with an isotherm depth of 22°C (midthermocline) [10].

2.5 Density calculation
Density is needed to calculate the Ekman pumping value in the area. The density is calculated uses the Gibbs function based on Equation 1 sourced from the TEOS-10 manual [11].

\[ \rho = \rho(S_A, t, p) = \left( \frac{g}{\rho} \right)^{-1} = \left( \frac{\partial g}{\partial \rho} \right)_{S_A, t}^{-1} \]

where,

- \( S_A \) = Absolute Salinity (g kg\(^{-1}\))
- \( t \) = In situ temperature (°C)
- \( p \) = Sea pressure (dbar)
- \( \rho \) = Density (kg m\(^{-3}\))
- \( g \) = Function of termodinamika Gibb’s
  \[ = h - (T_{n} + t)\eta \]

2.6 Ekman Pumping calculation
The data used for Ekman pumping calculations are surface salinity, surface temperature, and surface wind speed in the form of zonal and meridional components. Ekman pumping values are used to determine the strength index of upwelling. Kartadikaria (2011)[12] stated that the vertical velocity value of Ekman pumping can be calculated using the following formula:

\[ w_E = \left( \frac{1}{\rho f} \left( \frac{\partial \tau_x}{\partial y} \right) - \frac{1}{\rho f} \left( \frac{\partial \tau_y}{\partial x} \right) \right) \]

where

- \( w_E \) = \textit{vertical velocity of Ekman pumping} (m s\(^{-1}\))
- \( \tau_x \) and \( \tau_y \) = surface wind stress in x and y directions (kg m\(^{-1}\)s\(^{-2}\))
- \( f \) = parameter \textit{Coriolis} (s\(^{-1}\))
- \( \rho \) = water density calculated from salinity and surface temperature (kg m\(^{-3}\))
3. Results and Discussion

3.1. Vertical Speed Seasonal Variations Generated by Non-Local Factors (Remote Forcing)

The vertical speed generated by the remote forcing is obtained by reducing the Ekman pumping value caused by wind stress curl from the total vertical velocity of the SODA (averaged to a depth of 70 m) [12]. The results show that the intensity of upwelling in the Banda Sea is influenced by non-local factors (remote forcing), although the effect is not as large as local factors (Ekman pumping). At latitudes of 5.75 °S (Stations 2, 5 and 8) and 6.75 °S (Stations 3 and 6) it is seen that the remote forcing factor has a smaller effect than at latitude 4.75 °S (Station 1, 4, and 7) so that the total upwelling intensity of the SODA model results is not too different compared to the upwelling caused by local factors (Ekman pumping). The opposite situation happened in Station 9 where local factors were weaker than non-local factors so that the intensity of upwelling results from the SODA model tended to follow the pattern of non-local factors (remote forcing). In the eastern region (Stations 7 and 8) it is seen that local and non-local factors tend to weaken each other so that the intensity of the upwelling results of the SODA model is not as large as the western region (Stations 1, 2, and 3).

The results exhibit effect of remote forcing on the occurrence of upwelling in the Banda Sea. In this study it can be seen that the effect of remote forcing in the Banda Sea (-13 x 10^{-6} m / s - 14 x 10^{-6} m / s) is greater than that in the northern region of the Lombok Strait which ranges from -8 x 10^{-6} m /s - 11.6 x 10^{-6} m / s [12].

3.2. Ekman Pumping Seasonal Variations

The upwelling and downwelling in the study area was examined using Ekman pumping values. The Ekman positive pumping value (w_E > 0) indicates the occurrence of an upwelling, while the negative Ekman pumping value (w_E < 0) indicates the occurrence of a downwelling. An example of in Figure 3 presents monthly Ekman pumping overlays with thermocline depth for every station. The result shows that the duration of upwelling in the study area tends to be longer than the duration of downwelling. Upwelling in the study area generally started in April and ended in November, while the downwelling occurred in December - March. At Station 9, upwelling occurs through the year with weaker intensity in the northwest season (December - March).

In the Banda Sea, positive (negative) Ekman pumping occurs during Southeast monsoon (Northwest monsoon). In general, the strongest Ekman pumping occurs in July except at Station 1, 3, and 9. At Station 1 and 3, the strongest positive Ekman pumping intensity occurs in June, while Station 9 in September. The weakest Ekman pumping (w_E < 0) intensity occurred in February for all stations. During Northwest monsoon, a surface water mass transport from the waters around the Banda Sea to the northeast of the Banda Sea causing an increase in water mass with a fixed size of the Banda Sea cross section. An increase of water mass that occurs causes accumulation of a mass of water that will be offset by the movement of the water mass from the surface to the inner layer (downwelling). The opposite situation exists during Southeast Monsoon, where the water masses transport from the Banda Sea to the southwestern part which then spread to the waters around the Banda Sea. The reduction in water mass in the Banda Sea causes a vacuum of surface water mass that allows water from the inner layer to move to the surface (upwelling). A sill found in the Banda Sea is one of the factors that influence the process of upwelling and downwelling in the Banda Sea. The movement of the water mass towards the sill lifts up the water mass from the inner layer to the surface, while the movement of the water mass away from the sill causes the downwelling.

3.3. Thermocline Layer Seasonal Variations

In this study, the variation of thermocline layer depth was reviewed based on the depth of 22 °C isotherm layer which is considered to represent the mid-thermocline depth variation in the Banda Sea. The thermocline layer experiences the seasonal variations depending on the intensity of Ekman pumping. When Ekman pumping is negative (positive), the thermocline layer becomes deeper (shallow). This indicates a downwelling which exist in January - March and upwelling occur from
April – November. Thermocline layer in the western Banda Sea (Stations 1 and 2) are the deepest in March and February (Station 3), while in the eastern part of Banda Sea (Stations 7 and 8) the deepest thermocline layer is in January and March (Station 9).

In the central Banda Sea, Station 4 and both Stations 5 and 6 reach the deepest thermocline layer in February and in March, respectively. Oppositely during upwelling, the thermocline layer tends to reach the shallowest conditions in September except at Stations 1, 4, 7 and 8 where the thermocline layer shallowest in August. This represents the peak phases of the Southeast monsoon and September (Station 9) compared to other months. Monthly variations from the depth of the thermocline layer can be seen in Figure 3. The monthly variation in the thermocline layer depth is related to changes in SST, where SST becomes cooler along with shallower thermocline layers (upwelling). Figure 4 shows an example of the relationship between SST variations and thermocline depth at Station 1.

(a) Station 1

(b) Station 2

(c) Station 3
(d) Station 4

(e) Station 5

(f) Station 6

(g) Station 7
3.4. SST annual variations

El Niño and La Niña phenomena affect the inter-annual variation of SST and density. During El Niño, the SST (density) has a negative (positive) anomaly that indicates that the SST (density) is lower (heavier) compared to the average condition. While during La Niña, SST (density) anomaly is positive (negative) which shows a higher (lighter) SST (density) value than the average condition.

Tables 1a and 1b show SST anomalies and densities in the western part of the study area (Stations 1, 2, and 3), center (Stations 4, 5, and 6), and the eastern part (Stations 7, 8, and 9). Under normal conditions, SST (density) anomalies have small anomalies close to 0. During El Niño, SST (density) anomaly becomes more negative (positive) compared to normal conditions in November. While during La Niña, SST (density) becomes more positive (negative) compared to normal conditions in January, except SST at Stations 1, 2, 6, and 9.
Table 1a. SST anomaly during El Niño dan La Niña at Station 1 – 9

| Year | Month | St-1 | St-2 | St-3 | St-4 | St-5 | St-6 | St-7 | St-8 | St-9 | Condition |
|------|-------|------|------|------|------|------|------|------|------|------|-----------|
| 1993 | Jan   | 0.4  | 0.5  | 0.1  | 0.0  | 0.2  | 0.2  | 0.2  | 0.2  | 0.4  | Normal    |
|      | Nov   | -0.5 | -0.4 | -0.1 | 0.0  | 0.0  | -0.3 | -0.2 | 0.0  | -0.4 | Normal    |
| 1997 | Nov   | -0.9 | -0.8 | -1.0 | -0.9 | -1.1 | -0.8 | -0.7 | -0.7 | -0.6 | El Niño   |
| 1999 | Jan   | 0.4  | 0.1  | 0.2  | 0.2  | 0.4  | 0.1  | 0.3  | 0.3  | 0.2  | La Niña   |

Table 1b. Density anomaly during El Niño dan La Niña at Station 1 – 9

| Year | Month | St-1 | St-2 | St-3 | St-4 | St-5 | St-6 | St-7 | St-8 | St-9 | Condition |
|------|-------|------|------|------|------|------|------|------|------|------|-----------|
| 1993 | Jan   | 0.2  | 0.1  | 0.1  | 0.2  | 0.1  | 0.0  | -0.1 | -0.1 | -0.1 | Normal    |
|      | Nov   | 0.1  | 0.0  | 0.1  | -0.1 | -0.1 | 0.1  | 0.1  | 0.2  | 0.2  | Normal    |
| 1997 | Nov   | 0.6  | 0.7  | 0.6  | 0.5  | 0.6  | 0.6  | 0.5  | 0.4  | 0.5  | El Niño   |
| 1999 | Jan   | -0.4 | -0.4 | -0.3 | -0.4 | -0.4 | -0.3 | -0.2 | -0.2 | -0.3 | La Niña   |

The cross-correlation coefficient between two variables of SST (density) to ONI affirms a positive (negative) lag values. This indicates that conditions where SST (density) changes are faster (slower) than changes in ONI. It is known that SST and density anomalies changes have a negative time lag up to 1 - 2 months compared to the incidence of ENSO phenomena. Station 2 and station 3 have changes in SST and densities faster than other regions. The negative (positive) correlation coefficient for SST (density) exhibits that the El Niño phenomenon causes the SST (density) to be cooler (heavy). Time Lag for SST and density tends to have similar duration except at Station 1, 6, and 9 where the density changes faster than SST.

3.5. Thermocline Layer annual variations

To determine the effect of inter-annual phenomena such as El Niño and La Niña on changes in the thermocline layer and upwelling intensity, the thermocline depth and Ekman pumping anomalies during the period 1990-2008 represented Station 1 are overlaid with the ONI value, as displayed in Figure 5. The results illustrate that during the El Niño, the depth of the thermocline layer is negative (deeper), while during La Niña the thermocline depth is positive (shallower).
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The correlation coefficient values from the thermocline layer depth with ONI result in a significant negative correlation value (p-value <0.05). This indicates that the thermocline layer lift up to the surface along with the strength of El Niño (ONI ≥ + 0.5). On the contrary, the strengthening of La Niña (ONI ≤ -0.5) which cause the thermocline layer depth to become deeper. In addition, the results of the current study show that the ENSO phenomenon has the greatest influence on the thermocline layer depth in the eastern Banda Sea (correlation coefficient value, r = -0.7).

3.6. Ekman Pumping interannual variations

The ENSO phenomenon that varies every year leads to the annual inter-variation of Ekman pumping. Table 3 shows the comparison of Ekman pumping values under normal conditions, El Niño, and La Niña. In normal conditions, the Ekman pumping value varies and tends to have a negative anomaly value (-1.5x10⁻⁶ m/s - 1.1x10⁻⁶ m/s (January) and -0.9x10⁻⁶ m/s - 0.7x10⁻⁶ m/s (November)). In January, which coincided with La Niña, there is a large positive anomaly compared to January in normal conditions, while in November, which coincided with El Niño, it is seen that Ekman pumping has an anomalous value which is increasingly negative compared to November in normal conditions, except for the Station 4.

The phenomenon of weakening Ekman pumping intensity in the Banda Sea during El Niño is also found by [7] who found that during El Niño, SST in the Banda Sea was lower than the average

![Figure 5. Inter-annual variation of the depth anomaly of the thermocline layer (Black line) and Ekman pumping (Green dash) at Station 1](image)

Table 2. Interannual variation of thermocline depth anomaly at Station 1 – 9

| Year | Month | St-1 (m) | St-2 (m) | St-3 (m) | St-4 (m) | St-5 (m) | St-6 (m) | St-7 (m) | St-8 (m) | St-9 (m) | Condition |
|------|-------|----------|----------|----------|----------|----------|----------|----------|----------|----------|-----------|
| 1993 | Jan   | -13.9    | -4.2     | -3.7     | -20.6    | -22.8    | -15.1    | -24.7    | -24.7    | -14.8    | Normal    |
|      | Nov   | -10.1    | -5.4     | -0.4     | -17.6    | -15.9    | -17.8    | -25.6    | -27.4    | -24.2    | Normal    |
| 1997 | Nov   | -21.1    | -12.4    | -11.4    | -28.6    | -25.9    | -17.8    | -27.6    | -35.4    | -28.2    | El Niño   |
| 1999 | Jan   | 15.1     | 16.8     | 8.6      | 14.4     | 16.2     | 10.2     | 13.3     | 14.3     | 11.8     | La Niña   |
condition. The El Niño (La Niña) causes the thermocline layer to be deeper (shallower) than the normal conditions. The SST in the Banda Sea becomes cooler (warmer) accompanied by weaker (stronger) wind causing Ekman pumping to become weaker (stronger).

| Year | Month | St-1 | St-2 | St-3 | St-4 | St-5 | St-6 | St-7 | St-8 | St-9 | Condition |
|------|-------|------|------|------|------|------|------|------|------|------|------------|
| 1993 | Jan   | -1.5 | -0.3 | -0.1 | -0.2 | 0.0  | 0.1  | 0.4  | 0.8  | 1.1  | Normal     |
|      | Nov   | -0.9 | -0.8 | -0.7 | -0.6 | -0.5 | -0.6 | 0.7  | 0.0  | -0.4 | Normal     |
| 1997 | Nov   | -1.0 | -1.2 | -1.1 | -0.3 | -1.0 | -1.1 | 0.2  | -0.8 | -1   | El Niño    |
| 1999 | Jan   | 2.0  | 1.9  | 1.5  | 2.4  | 2.0  | 1.4  | 1.9  | 1.1  | 0.4  | La Niña    |

4. Conclusion
Upwelling intensity caused by local factors (Ekman pumping) generally occurs in April - November (0.8x10⁶ to 12.2x10⁶ m/s). Meanwhile, downwelling occurred in December - March with Ekman pumping values ranging from -0.2x10⁶ to -6.1x10⁶ m/s. Non-local factors (remote forcing) have a greater role to the strength of upwelling in the northern part of the Banda Sea (Stations 1, 4, and 7) with an intensity can reach 12.3x10⁶ m/s compared to the area in the center (Stations 2, 5, and 7) and south (Stations 3 and 6) with intensities reaching 4.1x10⁶ m/s. In the eastern part of Banda Sea (Station 7 and 8) and the northern part of Weber Deep, the influence of local factors (Ekman pumping) and non-local (remote forcing) tends to weaken each other so that the intensity of upwelling in the eastern region is weaker than the area in the center (Station 4, 5, and 6) and western regions (Stations 1, 2 and 3). During the northwest season, non-local factors (remote forcing) are stronger than local factors, causing weak upwelling, whereas during the southeast season local factors contribute more to causing upwelling in the Banda Sea. In the southern area of Weber Deep (Station 9) an anomaly occurs where Ekman pumping tends to be positive (upwelling) throughout the month with weak intensity and the remote forcing has more influence on the results of the vertical velocity of the model. Seasonally, the variation of the thermocline layer is more influenced by local factors, where when Ekman pumps positive (negative) the thermocline layer is shallower (deeper). SST is lower (higher) during El Niño (La Niña), while upwelling intensity (Ekman pumping) is weaker during El Niño than during La Niña. The response to the incidence of upwelling in the Banda Sea is 1 - 2 months later than the El Niño and La Niña events.

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