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The Thermocline Layer and Chlorophyll-a Concentration Variability during Southeast Monsoon in the Banda Sea

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Abstract. Thermocline layer and chlorophyll-a concentration can be used to investigate the upwelling region. This investigation is focused in the Banda Sea because the upwelling event in this area is quite large and has a longer upwelling duration than other waters in Indonesia. In addition, Banda Sea is also influenced by climatic factors such as monsoon. The aim of this research is to determine the validation of secondary data (from satellite imagery data and model) and in situ observation data (from research cruise) and to determine the variability of thermocline layer and chlorophyll-a concentration during Southeast Monsoon in the Banda Sea. The data used in this study were chlorophyll-a concentration, seawater vertical temperature at depths 0-400 meters, and sea surface temperature from remote sensing and in situ data. Spatial and temporal analysis of all parameters was conducted by quantitative descriptive method. The results showed that the variability of thermocline layer and the chlorophyll-a distribution were strongly related to seasonal pattern. In most cases, the estimates of thermocline layer and chlorophyll-a concentration using remote sensing algorithm were higher than in situ measured values. The greatest variability occurred in the eastern Banda Sea during the Southeast Monsoon with shallower thermocline layer, more abundance of chlorophyll-a concentration, and lower sea surface temperature.

Keywords: thermocline layer, chlorophyll-a, monsoon, upwelling

1. Introduction

The Indonesian Archipelago is so unique that it represents the only low latitude inter-ocean connection on the earth, with the Indonesian Trough Flow (ITF) communicating between the Pacific Oceans and Indian Oceans [1,2]. In relation to oceanography parameters such as sea surface temperature (SST), it has been suggested that complex feedback mechanisms may exist between the monsoons and the physical dynamics within the Indonesian Seas [3].

During the Northwest Monsoon, winds force the surface waters into the eastern archipelago, depressing the thermocline, while in the Southeast Monsoon, when dry air is brought from the Australian continent, the eastern seas is empty and there is evidence of large-scale upwelling events in the Banda Sea and elsewhere in the archipelago [1,4,5,6,7]. These upwelling events are one of the processes to control the productivity dynamics of the region. Whatever the mechanism for the upwelling event, there is an observable decrease of sea surface temperatures in the Banda Sea during the Southeast Monsoon [8]. For the eastern Indonesian waters, the southeastern wind prevails from April to November, with surface currents in the Flores Sea and Banda Sea directed westwards, whereas from December to March the northwestern wind reverses these currents to the east [30]. The seasonally changing hydrographic conditions in this area greatly influence the pelagic ecosystem, as indicated by monsoon-dependent changes in chlorophyll-a concentration and primary production and in zooplankton biomass. In the Banda Sea, the monsoonal periods coincide with upwelling and downwelling [1,4]. The Southeast Monsoon-induced westerly surface currents are partly fed by upwelling in the eastern Banda Sea, which results in nutrient enrichment of the photic layer. The northwest monsoon-induced easterly surface currents results in downwelling and oligotrophic conditions in the upper water layers. These changes in vertical movement in the water column chiefly concerned the upper 150 meters, while deeper layers remain relatively undisturbed [9].

In determining the oceanographic phenomenon, it's widely used data source from remote sensing or from in situ observation. Each data source has plus and minus. Remote sensing data are subject to several sources of error that affect their accuracy, for example calibration, atmospheric correction algorithm error, and problems in deriving parameter from radiances [10]. In situ data typically provide high quality and accurate data, but can only produce extremely limited spatial observations because of the expense of sea operation and the large area of the ocean. In situ data provide high quality and real information of parameter that satellite cannot, and satellite provide spatial and temporal observation that in situ cannot.

The analysis of time series is an important and valuable approach adopted in several studies for its ability to improve the spatial and temporal resolution of seasonal and inter annual pattern in biological and oceanographic data [11]. Moreover, information of the seasonal factor affecting the upwelling events in the Banda Sea is still limited. Therefore, a study on the variability of thermocline layer and chlorophyll-a concentration spatially over a prolonged period of time was urgently needed. This should be done in order to determine the validation of secondary data (from satellite imagery data and model) and in situ observation data (from IJEP research cruise). The final objective is to determine the variability of thermocline layer and chlorophyll-a concentration as upwelling indicator in the Banda Sea. This research focused in the condition during the Southeast Monsoon (June-July-August) until September.

2. Material and Methods

2.1. Study Area

The Banda Sea, lying in between the Flores Sea and the Arafura Sea, is a semi-closed waters in Indonesia. It comprises 3 major areas, the Northern Banda Basin with maximum depth 5801 meters in the northwest, the Southern Banda Sea Basin with maximum depth 5417 meters in the center, and the Weber Deep with maximum depth 7439 meters in the east. The study area was restricted to the area of 3^0S – 9^0S and 123^0E – 132^0 E (Figure1a). In this study, it was also used data from in situ observation using Baruna Jaya VIII Research Vessel as part of IJEP (Indeso Joint Expedition Program) cruise. This expedition was conducted in September 2016 across the northern area of Banda Sea, the Molucca Sea, and the Celebes Sea. The two survey stations for this study were arranged in 4.13^0 S 127.63^0 E and 3.38^0 S 127.34^0 E (Figure1b).

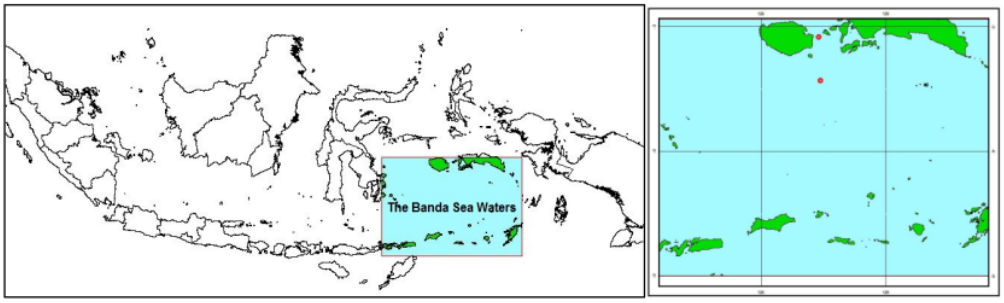

Figure 1. (a) Research study location of the Banda Sea, (b) The two red dots in the north indicate the stations of in situ observation as part of IJEP cruise

2.2. Data and Methods

Remote sensing data used in this research were monthly mean vertical sea water temperature, monthly mean chlorophyll-a concentration, and sea surface temperature as additional data. In order to make better description from time series data, this research used minimum 10-year-average of parameters observed. Monthly mean vertical sea water temperature data of 0-400 meters depth were extracted from SODA (Simple Ocean Data Assimilation) reanalysis for the period of January 1981 – December 2010. It now uses GFDL MOM5/SIS numerics at finer 0.25° x 0.25°x50 lev resolution, similar to the ocean component of the GFDL CM2.5 coupled climate model, and includes an active sea ice component. The Optimal Interpolation filter has also been augmented (relative to previous releases) with bias correction in order to allow for reduced bias in estimates of long term trends. Monthly mean Chlorophyll-a data were extracted from Aqua MODIS satellite data from July 2001 until December 2011. All data were in NetCDF format and were extracted using GrADS (Grid Analysis and Display System) software. We also delineated upwelling events based on the values of monthly mean sea surface temperature anomaly following the previous research method with 0^0 C > SST anomaly > -0.5^0 C as borders for upwelling initiation stage or termination stage and SST anomaly < -0.5^0 C as a border for fully developed stage of an upwelling event [12]. Monthly mean sea surface temperature data were extracted from SST Pathfinder from January 1981 – December 2010. To determine the bathymetry condition, we used Etopo1 bathymetry data from NGDC (National Geophysical Data Centre).

In situ observation was carried out during research cruise using Baruna Jaya VIII Research Vessel on September 2016. Profiles of sea water vertical temperature and chlorophyll-a concentration were obtained using CTD (conductivity, temperature, depth). Surface was defined by 0-10 meter depth. The water samples were collected at each observation station in various depths, filtered through Whatmann Cellulose Nitrate Membrane Filters 0.45µm and stored in cold storage room until further analysis in water quality laboratory. The chlorophyll-a concentration from all in situ observation station were quantified spectrophotometrically in absorbance at 630, 647,664, and 750 nm using formula (1) [13]:

$$C_a = 11.85\ (e_{664} - e_{750}) - 1.54(e_{664} - e_{750}) - 0.08\ (e_{630} - e_{750}) \qquad (1)$$

with C_a is concentrations of chlorophyll-a, respectively, mg/L; absorbance e_{630} ,e_{647} ,e_{664} are corrected optical densities at the respective wavelength (nm), and absorbance e_{750} is correction of turbidity (nm). After determining the concentration of pigment in the extract, then the amount of pigment per unit volume was calculated using formula as follows:

$$Chlo\ a, mg/m^3 = \frac{C_a\ x\ extract\ volume, L}{volume\ of\ sample, m^3} \qquad (2)$$

The variability of thermocline layer and chlorophyll-a concentration from remote sensing data and in situ observation were compared and determined spatially and temporally, especially during the

Southeast Monsoon (June-July-August) and second Transitional Monsoon (September-October-November). Generally, when the thermocline layer is shallower, sea surface temperature is lower, and chlorophyll-a condition is higher in abundance, so the upwelling condition is said to be happened.

3. Results and Discussion

3.1. Variability of the Thermocline Layer and Chlorophyll-a Concentration in the Banda Sea

3.1.1. Variability of the Thermocline Layer in the Banda Sea. The thermocline depth is defined as the depth of the maximum vertical temperature gradient. The depth of 20°C isotherm is widely used to represent the thermocline depth [14]. Moreover, the previous research found that the upper limit of thermocline layer in Indonesian waters were slightly shallower than it in equatorial Pacific [15], so the upper limit of thermocline layers were identified by 22^0C isotherm. Based on the 30-year-average SODA model data (1981-2010), the thermocline layer in the Banda Sea vary among region with the depth ranges between 85 until 130 meters (Figure 2).

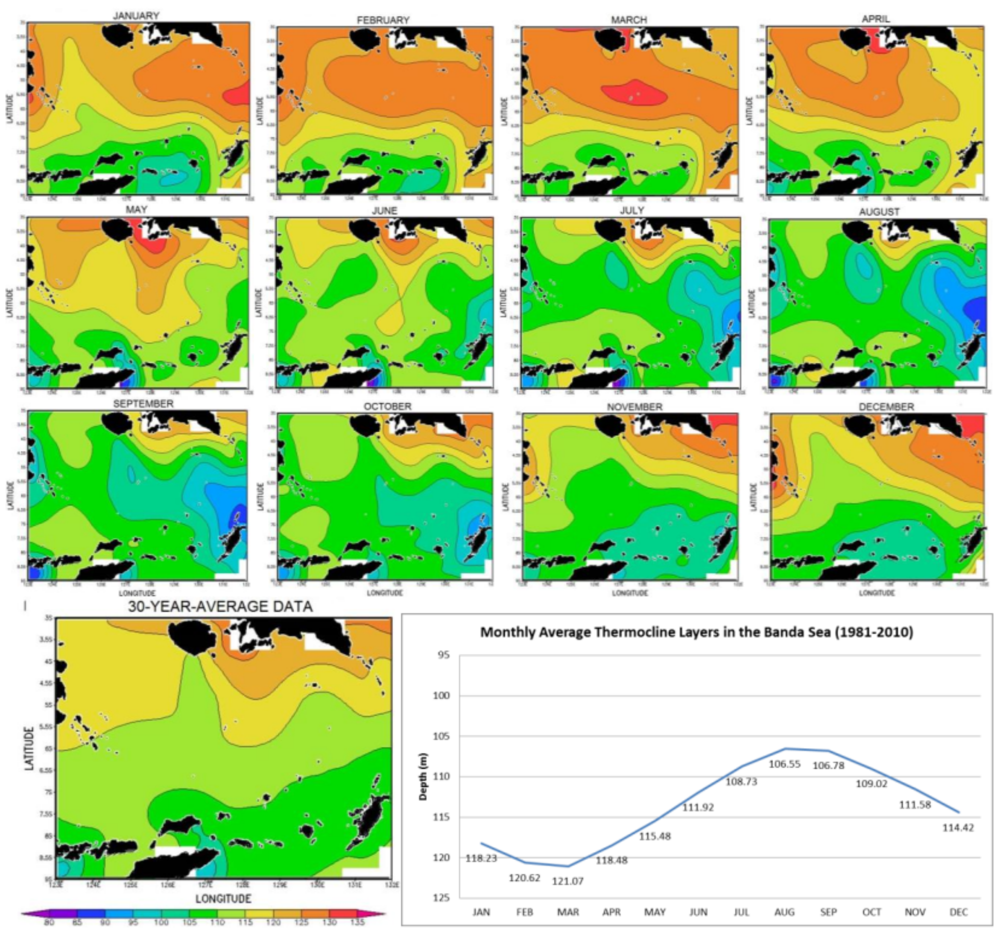

Figure 2. Spatial and temporal variability of Thermocline Layer in the Banda Sea

The variability of the thermocline layer is affected by monsoonal system as well as local and regional environment. In the Northwest Monsoon (wet season) occurred during December to February, the thermocline layer was seen only in the southern Banda Sea and deeper layer was seen in the most area of Banda Sea. The deepest thermocline layer was mostly reached in February until March. In the First Transitional Monsoon occurred during March to May, shallower thermocline layer was seen in the southern Banda Sea and extended to the eastern Banda Sea. In the Southeast Monsoon occurred during June to August, shallower thermocline layer was seen in the most area of the Banda Sea and reached the shallowest peak in the eastern Banda Sea. In the Second Transitional Monsoon occurred during September to November, shallower thermocline layer was seen in the southern and eastern Banda Sea but the area of shallow thermocline layer was narrower as the depth of thermocline began to rise. In general, the fluctuation of thermocline layer depth seemed to follow the seasonal pattern.

The upwelling period in the Banda Sea occurred from April through December. Moreover, they calculated the Ekman pumping upwelling was 1,27Sv. [7]. Wind stress curl induces Ekman upwelling from April to December, with weaker downwelling for the rest of the year [4]. This condition is followed by the shallow thermocline layer in the Banda Sea [7]. The thermocline layer temporal variability in Figure 2 showed that the initial of thermocline shoal was in April and tended to be shallower until September. The highest variability in this research was seen in the eastern Banda Sea. Easterly wind occurred during the Southeast Monsoon and brought water mass from the eastern Banda Sea caused the water mass gap in that area. The water mass from deeper layer uplifted to the surface through the upwelling event [4,16]. Therefore, the eastern Banda Sea tends to be the location of the greatest upwelling event in the Banda Sea.

3.1.2. The Variability of Chlorophyll-a Concentration in the Banda Sea. The variability of chlorophyll-a concentration in the Banda Sea was described by the comparison of remote sensing data (from Aqua MODIS satellite data) and in situ data. The time series of monthly composites Aqua MODIS data was from 2001 until 2011. The sea surface chlorophyll-a concentration vary among the region of the Banda Sea, so it will be easy to determine the variability of the parameter using spatial and temporal analysis.

A relatively high concentration and wide distribution of sea surface chlorophyll-a was obviously seen during April to August. During this period, high concentration of chlorophyll-a in the eastern area tends extend to the center and western area of the Banda Sea. The spatial and temporal distribution of chlorophyll-a concentration (Figure 3) also showed the evidence of a difference between the character and dynamics of the eastern and western Banda Sea. The eastern Banda Sea exhibit the highest chlorophyll-a concentration up to 1 mg/m^3. The area near the island showed high concentration of chlorophyll-a. This situation indicated that marine productivity within this area was governed by nutrient load from the river and coastal discharge. Moreover, that condition also indicated that the upwelling event is controlled by monsoonal system. The chlorophyll-a distribution pattern indicates the gradation value that is high in coastal areas, especially estuary and getting lower toward the open sea. High concentrations in the area near of the islands were caused by the accumulation of nutrients that come from rivers and inputs from land runoff [17,18,19].

The monthly average chlorophyll-a concentration in the Banda Sea ranged from 0.11 to 0.43 mg/m^3. The maximum peak is in June, meanwhile the minimum peak is in February, March, September, and October (Figure 3). This condition is consistent with upwelling event that occurred in April to December [20]. In general, the abundance of chlorophyll-a concentration datasets didn't follow the seasonal pattern. This meant that the local effect gave stronger influence than monsoonal effect. But, the chlorophyll-a distribution still follow the monsoonal effect. The patterns of chlorophyll-a distribution was usually controlled by the seasonal monsoon [12,21,22,23]. The datasets from remote sensing data (SeaWiFS data) and field data support the idea that upwelling during the Southeast Monsoon dominates the east/west distribution of chlorophyll-a, and supports higher phytoplankton biomass (and therefore, shallower euphotic depths) in the eastern Banda Sea [8].

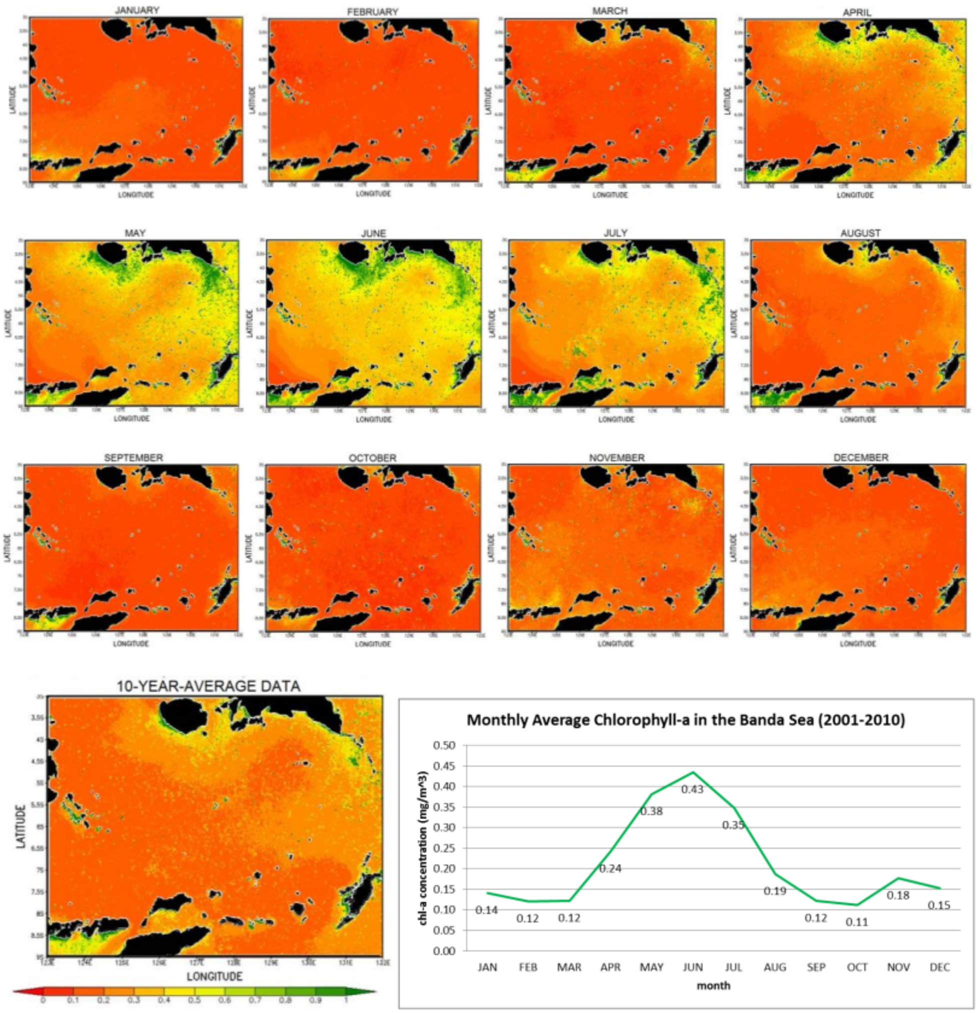

Figure 3. Spatial and temporal variability of Chlorophyll-a concentration in the Banda Sea, from 10-year-average Aqua MODIS data (2001-2010)

3.2. The Comparison of In Situ and Remote Sensing Data

The IJEP (INDESO Joint Expedition Program) cruise was carried out aboard the Indonesian Research Vessel, RV. Baruna Jaya VIII. The northern area of Banda Sea was identified by Station 1 and Station 2. We used CTD data to determine the sea vertical temperature and chlorophyll-a concentration.

Based on the in situ observation using CTD Rosettes, the 22^0C isotherm existed in various deep, depend on the bathymetry condition. The thermocline layer in station 1 was shallower than that of in station 2. The comparison of SODA model data and in situ data from CTD showed that SODA model data algorithm over-estimated the thermocline layer up to 1.4 times (Figure 4). Based on this result, the thermocline layer in 2016 was shallower for about 34 meters depth than the average condition (1981-2010). Although there are difference between the thermocline layer from SODA model data and CTD data (in situ), but the value seems to be linear (Figure 4).

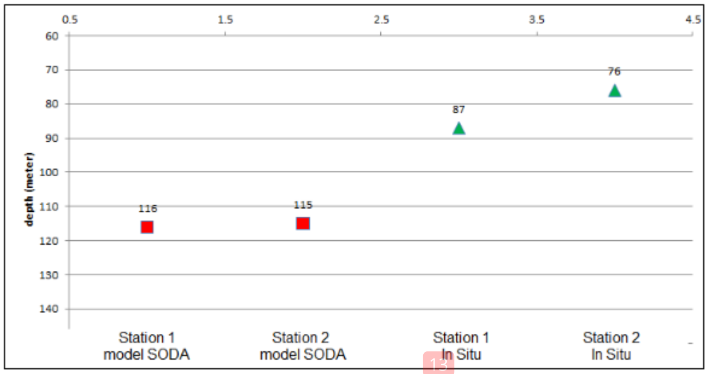

Figure 4. The comparison of thermocline layer from in situ and remote sensing data (SODA model data)

The good performance was also shown by the comparison of chlorophyll-a concentration. The comparison of Chlorophyll-a concentration from in situ data and remote sensing data (Figure 5) showed that the value of in situ data was lower than the remote sensing data, but the value seems to be linear. This indicates overall good performance of Aqua MODIS data compared with in situ data. In previous research, Aqua MODIS data also has a strong relation with in situ data up to 80% [18].

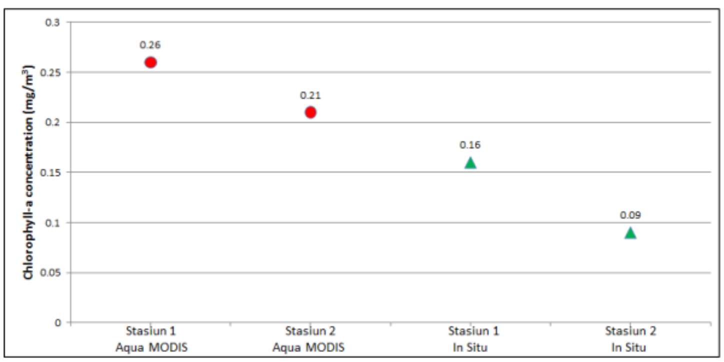

Figure 5. The comparison of chlorophyll-a concentration from in situ and remote sensing data (Aqua MODIS data)

According to the result shown, the chlorophyll-a concentration from Aqua MODIS data seemed to over-estimate the in situ data up to twice. Based on this result, the chlorophyll-a concentration in 2016 was less abundant for about 0.11 mg/m^3 than the average condition (2001-2011). In situ data used the 10 meter depth chlorophyll-a data, meanwhile the remote sensing data used the sea surface chlorophyll-a data. Supposedly, this was the reason why there was difference between in situ and remote sensing data in this research.

Many researchers exhibit the same problems. Remote sensing data may over-estimate coastal chlorophyll, with values 30%–77% higher than the next closest climatology [21]. Remote sensing data of chlorophyll-a SeaWiFS over-estimated chlorophyll-a (up to six times) at stations near the turbidity front and in the Rıo de la Plata Estuary waters, but provided adequate estimates (within 10%) in the subtropical waters of the Brazil Current [22]. Moreover, although remote sensing data were always higher than the other datasets in the open ocean, the relatively small differences could be due to natural variability.

In general, when comparing the in situ and satellite derived data, one has to remember that both kinds of estimates are subject to errors. In situ water determinations are subject to several potential sources of errors and need for further improvement in the methodology. More importantly, on a qualitative level, the remote sensing data for all parameters showed similar patterns to those seen in the in situ observation (Table 1).

Table 1. The comparison of all parameters from In Situ and remote sensing data

Observation Parameters in September		Station 1	Station 2
Chlorophyll-a (mg/m^3)	In Situ Data	0.156	0.088
	Aqua MODIS data	0.262	0.209
Thermocline Layer (meter)	In Situ Data	93	108
	SODA data model	115	116

3.3. Variability of the Thermocline Layer and Chlorophyll-a Concentration as the Upwelling Indicator in the Banda Sea

To determine the variability of the parameters, we used the anomaly value. The negative anomalies of monthly average thermocline layer describe the thermocline shoals, meanwhile the positive anomalies describe the thermocline sinking. The thermocline layer anomaly showed that the thermocline shoal ranged 10 – 20 meters. The greatest anomaly occurred in the eastern Banda Sea during Southeast Monsoon. The thermocline started to be deeper during the second Transitional Monsoon (Figure 6). The maximum variability of thermocline layer depth showed in the center until eastern area of the Banda Sea during Southeast Monsoon (Figure 6a) and mostly showed in the eastern area of Banda Sea during Second Transitional Monsoon (Figure 6b). The southern and northern area of Banda Sea showed minimum variability since the thermocline layer depth remains shallow along the year.

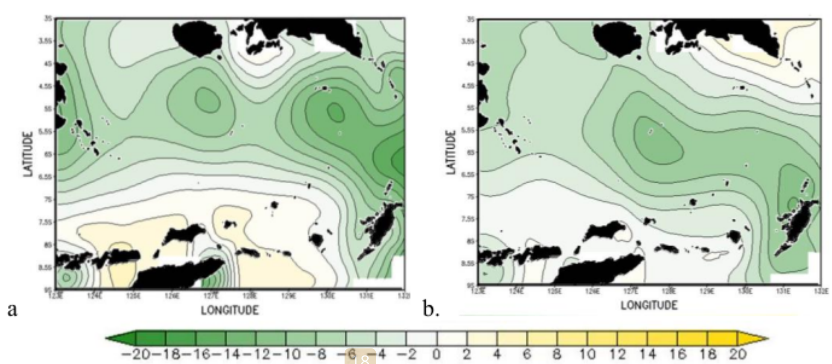

Figure 6. The thermocline layer anomalies in the Banda Sea, derived from SODA model data (1981 – 2010) during (a) Southeast Monsoon (JJA) (b) Second Transitional Monsoon (SON)

The variability of thermocline layer is affected by monsoonal system. Shallower thermocline layer that mostly occurred in the southern and northern area of Banda Sea (Figure 6) was supposedly caused by the difference in bathymetry condition. The southern area is surrounded by islands with 2000 meters of the maximum depth. Meanwhile, the other area of Banda Sea has higher depth up to more than 7000 meters (Figure 7). The maximum variability of thermocline layer mostly occurred in the deepest area of the Banda Sea (the eastern Banda Sea).

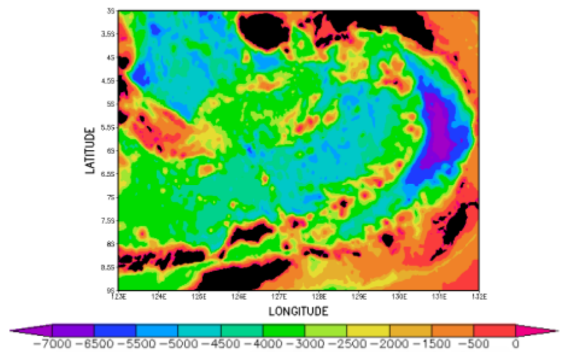

Figure 7. Bathymetry condition in the Banda Sea

The positive anomalies of monthly average Aqua MODIS data describe the more abundance of chlorophyll-a concentration, meanwhile the negative anomalies describe the less abundance. The range of chlorophyll-a concentration was -1 until 1 mg/m^3. The chlorophyll-a concentration seemed to be higher during Southeast Monsoon (Figure 8a) than during Second Transitional Monsoon (Figure 8b). This condition is consistent with monthly average chlorophyll-a concentration (Figure 3).The highest variability of chlorophyll-a concentration occurred mostly in the eastern Banda Sea and extended to the center area during Southeast Monsoon. During the Second Transitional Monsoon, the chlorophyll-a concentration variability started to decrease.

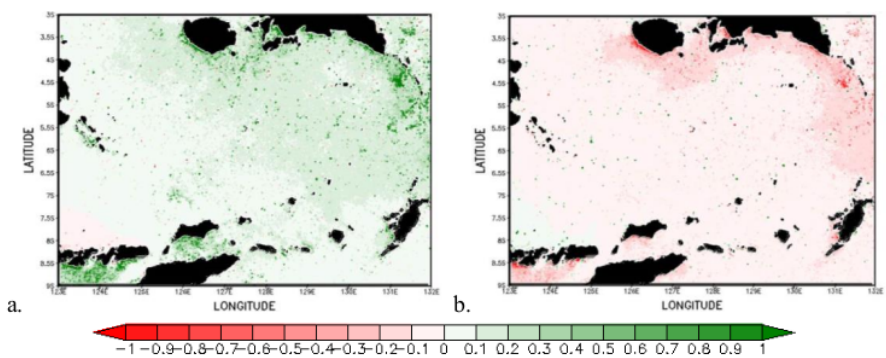

Figure 8. The chlorophyll-a anomalies in the Banda Sea, derived from Aqua MODIS data (2001 – 2010) during (a) Southeast Monsoon (JJA) (b) Second Transitional Monsoon (SON)

We also used sea surface temperature from SST Pathfinder (1981-2010) as an additional data. Sea surface temperature has the close relationship with layer of sea water [24]. Accordingly, sea surface temperature data can be used to interpret the phenomenon (such as thermal front, currents, upwelling, and biological activity) that occurred in the ocean [25,26]. According to previous research, the high value of sea surface temperature mostly occurred during Northwest Monsoon, and the low value of sea surface temperature mostly occurred during Southeast Monsoon. The temperature difference of west area minus east area of the Banda Sea calculated was 2^{0}C [27]. Moreover, the upwelling event can be determined from the sea surface temperature anomalies. Based on the data processing of SST Pathfinder (1981-2010), the upwelling initiation in Banda Sea typically occurred in May and fully developed upwelling event occurred in June and the largest upwelling event occurred in August. The average sea surface temperature in the Banda Sea is 28,34^0 C.

Based on the anomaly of all parameters in the Banda Sea, it can be seen that in general, upwelling event supposedly occurred in May until August. During those periods, the chlorophyll-a concentration was increasing, meanwhile the thermocline layer and sea surface temperature was decreasing (Figure 9). This condition can be inferred as upwelling event. This value might be different in other cases, depend on the time series used in the data processing and the number of in situ stations observed. In general, this result was consistent with previous research that in the south of East Java and Banda Sea have upwelling with longer duration (3–4 months) and higher intensity (decrease in temperature reached >2°C below average), the primary productivity was higher than other locations [28].

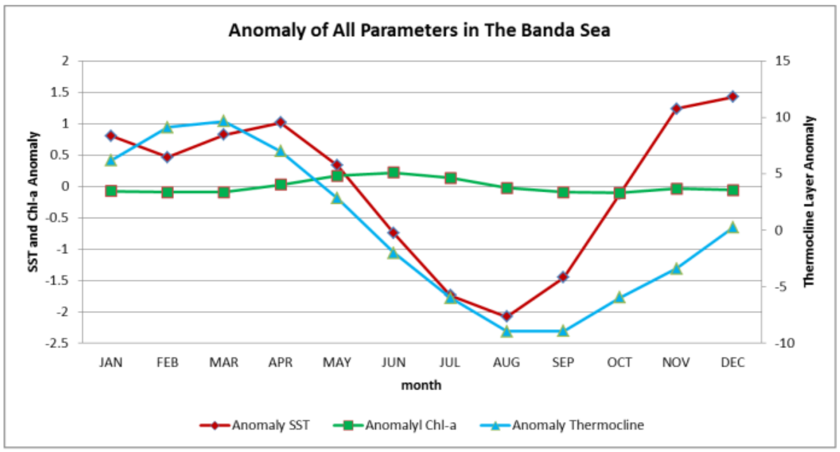

Figure 9. Anomalies of All Parameters in The Banda Sea, Sea Surface Temperature were derived from SST Pathfinder data, Chlorophyll-a concentration was derived from Aqua MODIS data, Thermocline layer (22^{0}C isotherm) is derived from SODA model data.

It is also the evidence that upwelling did occurred during the Southeast Monsoon. If the upwelling is strong or continues for a sufficient length of time, the thermocline eventually breaks the surface and is then seen as a front along the coast which moves back and forth depending upon the strength of the upwelling. The upwelling is described with the shallower thermocline upper limit, the lower sea surface temperature, and the higher chlorophyll-a concentration compared with the monthly average value. Moreover, the sea surface chlorophyll-a concentration has a strong correlation with fish productivity [17,29] and other biological parameters, for example the micro nekton of the Banda Sea showed in general larger spatial variability in numbers and biomass in August than in February [30]. To determine this case, it is needed an advance and further analysis.

4. Conclusion

The remote sensing data seemed to be overestimated nearly double the value of in situ data, but they showed similar patterns (linear) with in situ data. The variability of thermocline layer, sea surface temperature, and chlorophyll-a distribution was strongly related to seasonal pattern, although the local effect gave more influence in the abundance of chlorophyll-a concentration. In general, the upwelling event occurred in May until August (during Southeast Monsoon) in The Banda Sea. The Southeast Monsoon dominates the east/west distribution of chlorophyll-a, shallower thermocline layers and lower sea surface temperature, especially in the eastern Banda Sea.

5. Acknowledgement

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