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Halmahera Eddy Features Observed from Multisensor Satellite Oceanography

[1]G. Harsono, [1]A.S. Atmadipoera, [2]F. Syamsudin, [1]D. Manurung and [1]S.B. Mulyono
[1]Department of Marine Science and Technology, Faculty of Fisheries and Marine Science, Bogor Agriculture University (BAU), Jl. Agatis, Lingkar Akademik Kampus IPB, Bogor, 16680, Indonesia
[2]Agency for the Assessment and Application of Technology (BPPT), Jl. MH. Thamrin No. 8, Jakarta Pusat, 10340, Indonesia

Corresponding Author: G. Harsono, Department of Marine Science and Technology, Faculty of Fisheries and Marine Science, Bogor Agriculture University (BAU), Jl. Agatis, Lingkar Akademik Kampus IPB, Bogor, 16680, Indonesia

ABSTRACT

This study performs novel approach to identify Halmahera Eddy (HE) features using multisensors satellites oceanography, hydrographic data and skipjack tuna (*Katsuwonus pelamis*) during 2002-2012. The results show that anticyclonic HE has high chl-a concentration in the outer ring of eddies with averaged horizontal diameter of 520 km and shifts along southeast-northwest axis of 392 km. Seasonal and interannual variability have dominant influences in increasing (decreasing) diameter of eddy during the southeast (northwest) monsoon and shifting of eddy during El Nino (La Nina) event, respectively. These HE patterns are also consistent with deepening of subsurface temperature layer and high gradient of salinity front around the HE periphery. Meridional shifting of HE has significant impact of productivity with skipjack tuna catch, which show movement northward (southward) from its center HE at 4N correlate with increasing (decreasing) catch. This implies that during the northwest monsoon and La Nina event, skipjack tuna catch increase in the western tropical Pacific waters.

Key words: Anticyclonic Halmahera eddy, translation, seasonal and interannual variability, meridional shifting, skipjack tuna catch

INTRODUCTION

Northern water of West Papua is considered as western part of warm pool Pacific Ocean and has been known having complex oceanography in term of dynamics and marine biology (Fine *et al*., 1994; Christian *et al*., 2004). This water is a crossroad of water mass and current system, so called “the low latitude western boundary currents”, that consist of southward Mindanao Current (MC), northwestward New Guinea Coastal Current (NGCC) and New Guinea Coastal Undercurrent (NGCUC). Retroflections of these currents to be North Equatorial Counter Current (NECC) in northeastern Halmahera island create a quasi-persistent anticyclonic circulation of Halmahera Eddy (HE) and minor cyclonic Mindanao Eddy (ME) (Kashino *et al*., 2013). The currents bring water masses from the North and South Pacific subtropical gyres but southern hemisphere water masses are dominant in HE region, supplied by NGCC/NGUC as the prolongation of South Equatorial Current (SEC) (Fine *et al*., 1994; Kashino *et al*., 2007). Figure 1 displays schematic diagram of current system in this region.

The existence of both eddies are related to global ocean dynamics and water mass transports play important role in the water mass exchange, heat and salinity among the oceans

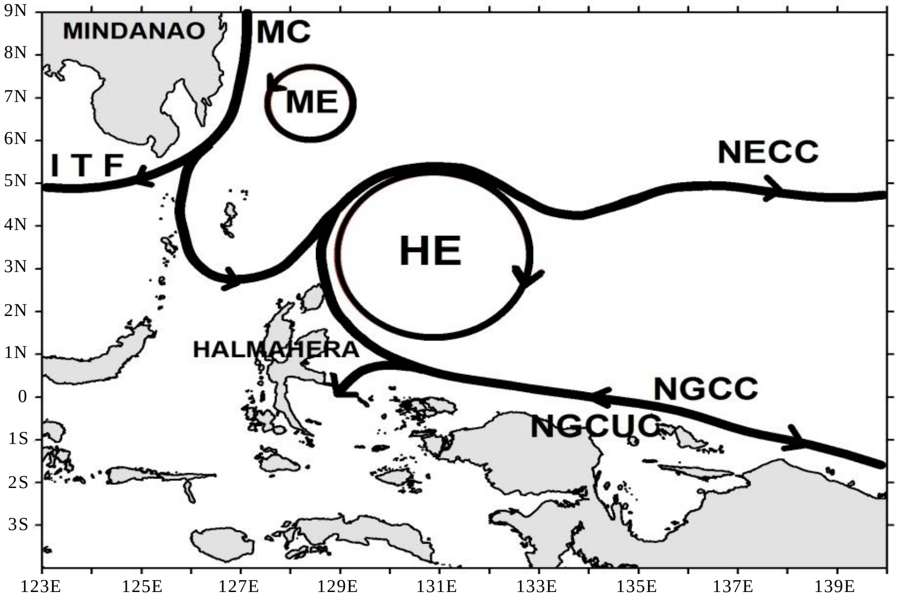

Fig. 1: Schematic diagram of current system in the western tropical Pacific Ocean. MC: Mindanao current, ME: Mindanao sddy, HE: Halmahera eddy, NECC: North equatorial counter current, NGCC: New guinea coastal current, NGCUC: New guinea coastal undercurrent, ITF: Indonesian throughflow (Fine *et al*., 1994; Kashino *et al*., 2013)

(Atmadipoera *et al*., 2004). The eddies have been studied in different time scales based on surface drifter, hydrographic survey, mooring line and satellite altimetry data (Lukas *et al*., 1991; Kashino *et al*., 1999, 2013; Heron *et al*., 2006). Halmahera Eddy (HE) seems to play more important role in the circulation, heat and salinity exchanges in the western tropical Pacific compare to Mindanao eddy (Kashino *et al*., 2013). HE has its center around longitude 130°E with depth of 50 m and horizontal scale of 500 km and with increasing depth, its center shifts to the North with smaller horizontal scale to be 300 km at depth of 350 m. HE also plays important role to control water South Pacific water masses brought by NGCC entering the internal Indonesian water as part of Indonesian Throughflow (ITF) (Arruda and Nof, 2003; Kashino *et al*., 2013).

HE also has a high relationship with the increasing marine productivity in its surrounding waters, eventhough, this study has been less described until recently. In general, the clockwise eddy of HE could develop an indentation that filled by less dispersed chlorophyll (chl-a) concentration and warm water from the NGCC. However, in the outer ring of HE, a high chl-a related to enrichment of nutrients due to high turbulence along the isopycnal slope may be seen. This outer ring of the HE controls the structure of phytoplankton community (Kai and Marsac, 2010). Interaction between cyclonic and anti-cyclonic eddies could generate what so called “local front jet” that could make fragments of high intensity of biological activities (Kang *et al*., 2004). This is why, the existence of HE could be as a proper proxy for the higher marine productivity hotspot compare to the surrounding regions.

Investigation of current pattern by tracking chl-a distribution in the western equatorial Pacific had been done by Christian *et al*. (2004). They found that chl-a blooming could have meanders along NECC axis spanning until 2000 km in the images of Sea WiFS satellite during El Nino 1997/1998 event. This inductive environmental typology has given an idea to study HE features and its movements through observation of marine productivity proxies using multisensors satellite oceanography. This study could observe HE development through chl-a tracking to understand its dynamics and further to correlate them with potential hotspot for fishing activities in this region. In order to achieve this objective, we utilized imagery data set from multisensors satellites of MODIS to obtain chl-a, JASON-1 for sea surface height anomaly and hydrographic data from Tropical Ocean Climate Study (TOCS) program of Japan Agency for Marine-Earth Science and Technology (JAMSTEC) and Agency for the Assessment and Application of Technology (BPPT) Indonesia collaborative research.

This study aims to investigate HE movement pattern as response of ocean-atmosphere dynamics in the western equatorial Pacific using chl-a features taken from multisensors satellites oceanography and to correlate relationship between HE shifting with the skipjack (*Katsuwonus pelamis*) catches in the fishing ground around Morotai island in the Indonesian territorial waters near the center of HE.

MATERIALS AND METHODS

Study area: The study area covers the western part of western equatorial Pacific between Mindanao and Papua as shown in Fig. 2.

The method approach is a descriptive and qualitative analyses using multisensor satellites comparison of chl-a features and HE movements indicated by satellite JASON, as well as, by hydrographic archive data of using CTD and skipjack tuna catch of total production per month and HE latitudinal movement.

Surface chl-a concentration: Sea surface chlorophyll-a concentration imagery was obtained from satellite Aqua MODIS Level-3 SMI (Sea DAS Mapped Image) 8-days composites with spatial

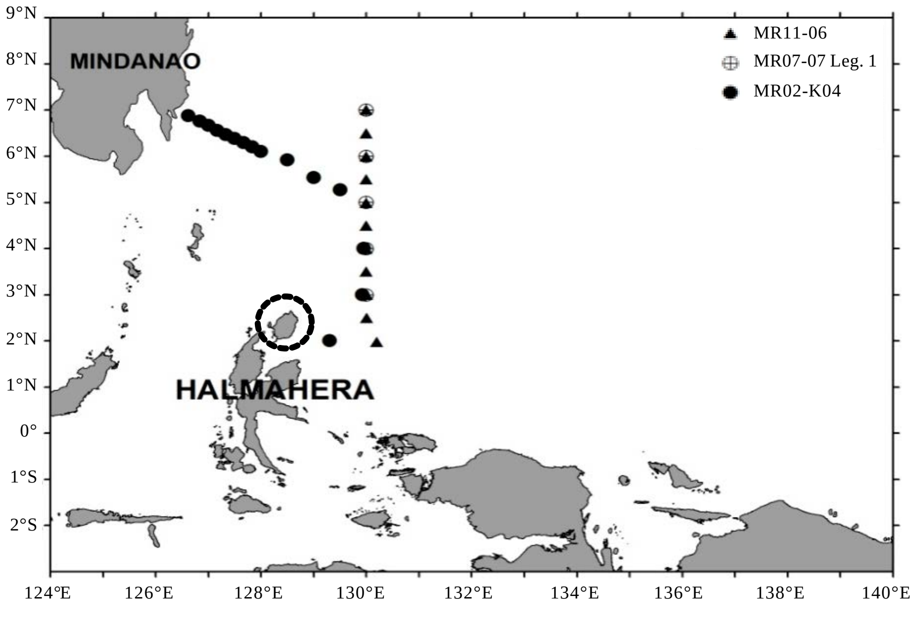

Fig. 2: Study area in the western equatorial Pacific waters. Black symbols denote hydrographic stations during different cruises from the Tropical Ocean Climate Study (TOCS). The coverages of multi-sensors satellites oceanography are set to 3S-9N and 124E-140E and skipjack tuna catch areas shown as the black dash line circular

Table 1: Three hydrographic data used in this study from the Tropical Ocean Climate Study (TOCS) cruises

Cruise code	Period	Season	ENSO event
MR02-K04	July-August 2002	Summer	El Nino
MR07-07 Leg. 1	January 2008	Winter	Normal
MR11-06	August-September 2011	Summer	La Nina

resolution of 4×4 km. These data was downloaded from Distributed Active Archive Center (DAAC) NASA Goddard Space Flight Center (GSFC) through website address: http://modis.gfsc.nasa.gov/data. The chl-a data was monthly averaged in order to identify chl-a features formed by HE movement.

Hydrographic data: From TOCS cruises of JAMSTEC and BPPT cooperation, 8 hydrographic data sets were used in this study to analyze sub-surface property structure of HE. The data include shipboard Acoustic Doppler Current Profiler (ADCP), Conductivity Temperature Depth (CTD) and expendable CTD (Table 1). The data was quality controlled by routine calibration, correction and filtering, performed by Data Management Office (DMO) Yokohama Institute for Marine Science JAMSTEC.

Skipjack tuna catch data: Total catches of skipjack tuna (*Katsuwonus pelamis*) were taken from the office of Ocean and Fisheries of North Halmahera Regency, North Maluku province. This data was composed of total landing fishing sites in Morotai islands, Indonesia during January 2011-March 2012. The class of fishing boats possesses 5-10 gross tonnage with one trip fishing of 1-2 days. Fishing gears used by the fishermen were mainly purse seine, huhate (pole and line) and funae (similar to pole and line).

RESULTS

Halmahera eddy features: The presence of HE was clearly seen from near-surface current vector, as clockwise circular motions, where northern edge water mass flowing eastward in contrast to southern edge toward the West (Fig. 3). This current eddies dissipate the energy of currents by friction, implying a pinch off of distinct properties characteristics of water mass and creating a hole of less chl-a concentration within the eddy. In other words, high surface chl-a appears to converge along its outer ring (Fig. 3). This high chl-a ribbon may also be fed directly from high chl-a water mass of Maluku Sea.

During El Nino, Normal and La Nina events of 2002, 2008 and 2011, respectively, the locations of HE center, diameter and shifting were changed (Fig. 3). During El Nino 2002 event (Fig. 3a), HE moved southeastward with its center near 3N,131E and diameter 500 km but during Normal year 2008 event (Fig. 3b), HE shifted northwestward with its center near 4.5N,128E and diameter of 300 km. During La Nina event of 2011 (Fig. 3c), HE shifted farther North with its center near 5N, 129E and diameter of 500 km.

Vertical structure of Halmahera eddy: Figure 4 presents cross-section of temperature and salinity across the HE region during El Nino, Normal and La Nina events of 2002, 2008 and 2011, respectively (Table 1). During El Nino 2002 event (Fig. 4a), mixed layer depth deepened to 75 m with the temperature range between 28-29°C (Fig. 4a) and termocline depth varied from 75-350 m and temperature between 27-10°C, where high vertical gradient of temperature lied at

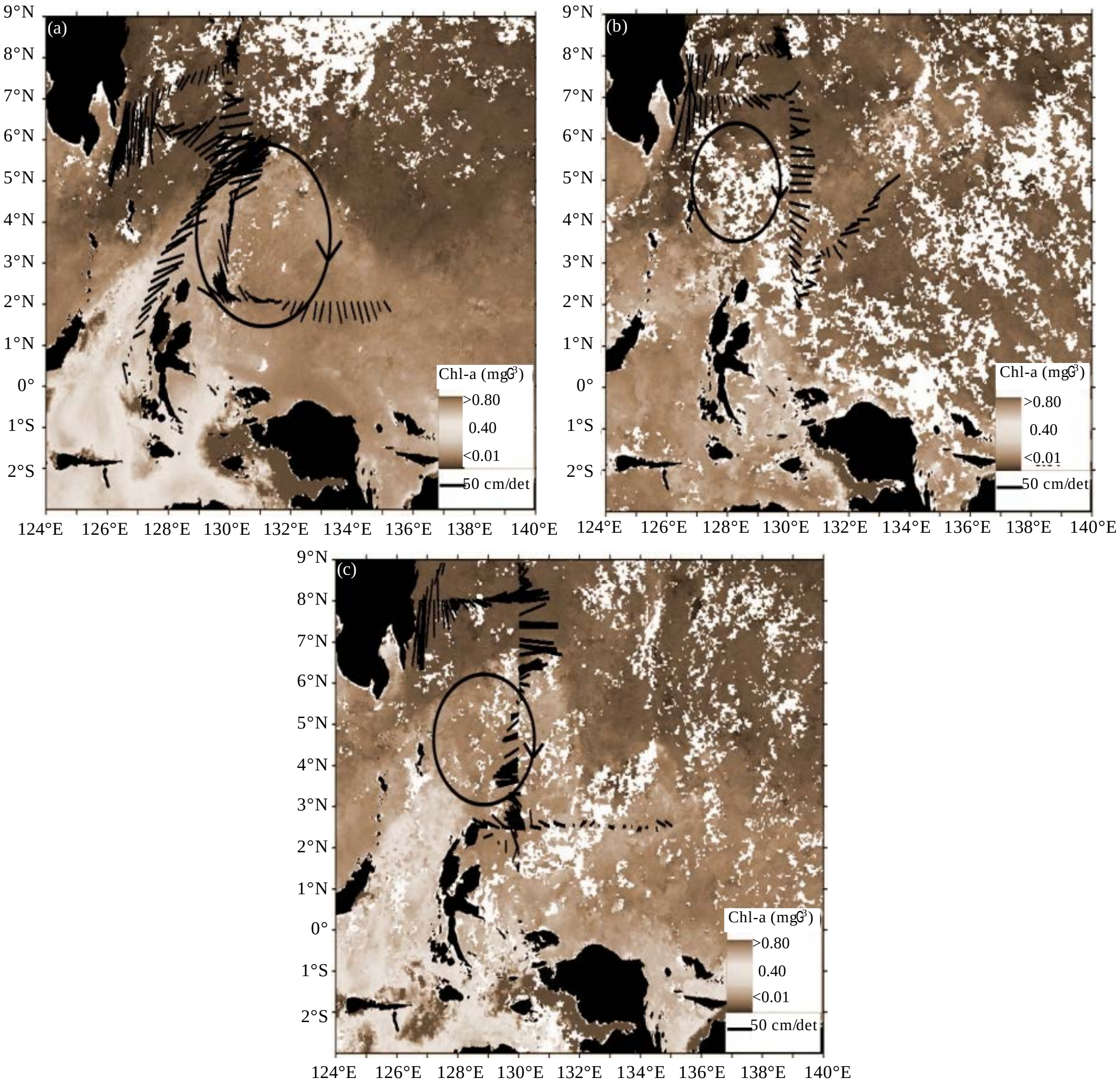

Fig. 3(a-c): Monthly average of surface chl-a concentration (mg m^{-3}), overlayed with 50 m depth current vectors derived from shipboard ADCP during TOCS cruises of (a) El Nino event in July-August 2002, (b) Normal year in January 2008 and (c) La Nina event in August-September 2011

the middle thermocline layer. It is revealed that isotherms near 3-4N were suppressed downward and tilted farther North with deeper depth associated with anticyclonic HE dynamics. High horizontal gradient of temperature localized in the northern section, where northern hemisphere water exists. Vertical structure of salinity confirms predominance of southern hemisphere water masses in the HE region, where high salinity (>35 psu) South Pacific Subtropical Water (SPTW) occupies South of 5N.

During Normal year of 2008 (Fig. 4b), mixed layer varies between 50-75 m depth and thermocline layer between 50-300 m depth, which was shallower than that observed during El Nino 2002 event (Fig. 4a). It is consistent that northward tilt of isotherms with deepening depth of HE is also observed during this period. However, high saline SPTW seems to be much more diluted South of 5N.

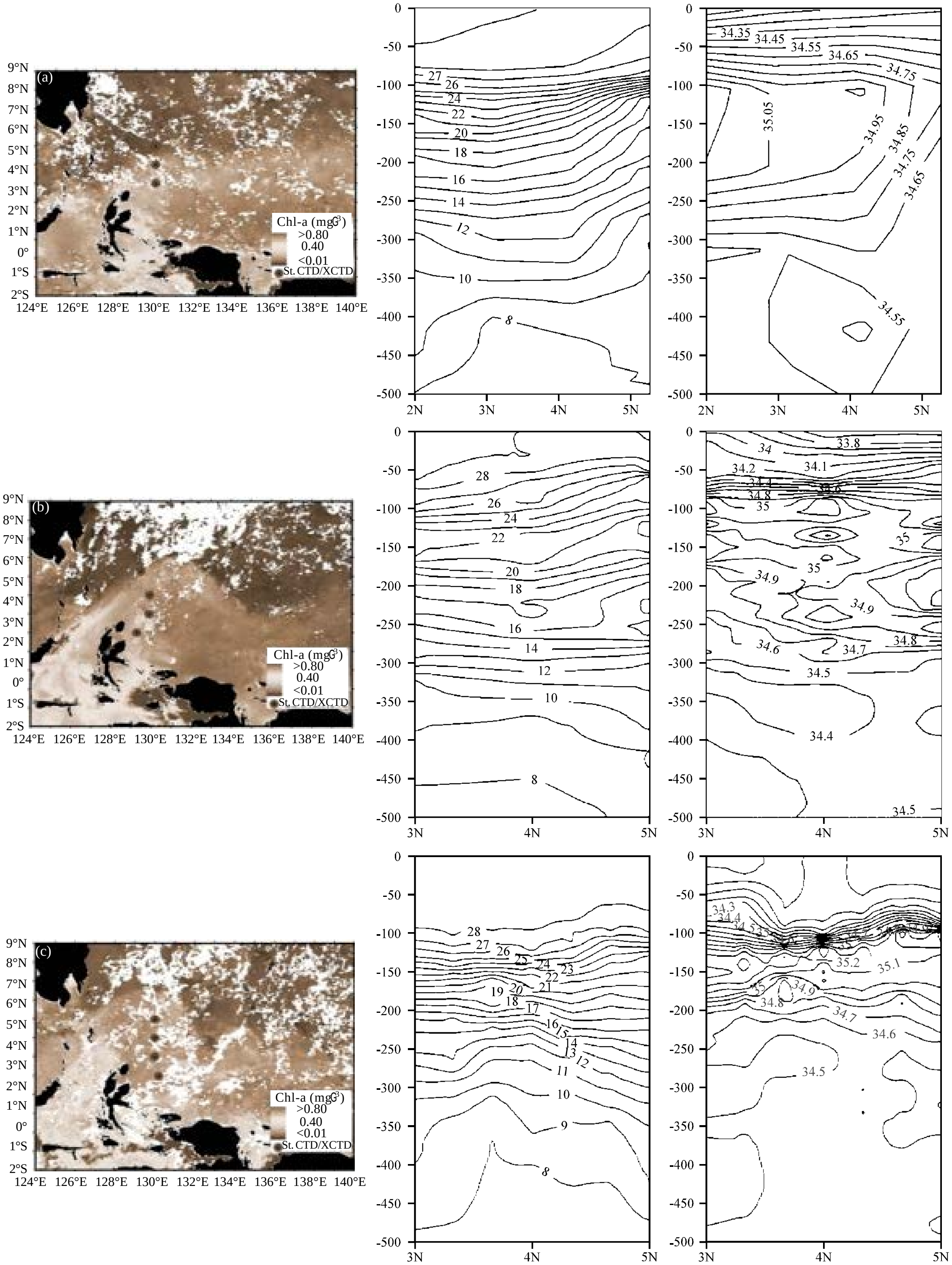

Fig. 4(a-c): Vertical structure of temperature and salinity from three TOCS cruises in the western equatorial Pacific during, (a) TOCS cruise 2002 (El Nino year), (b) TOCS cruise 2008 (Normal year) and (c) TOCS cruise 2011 (La Nina year)

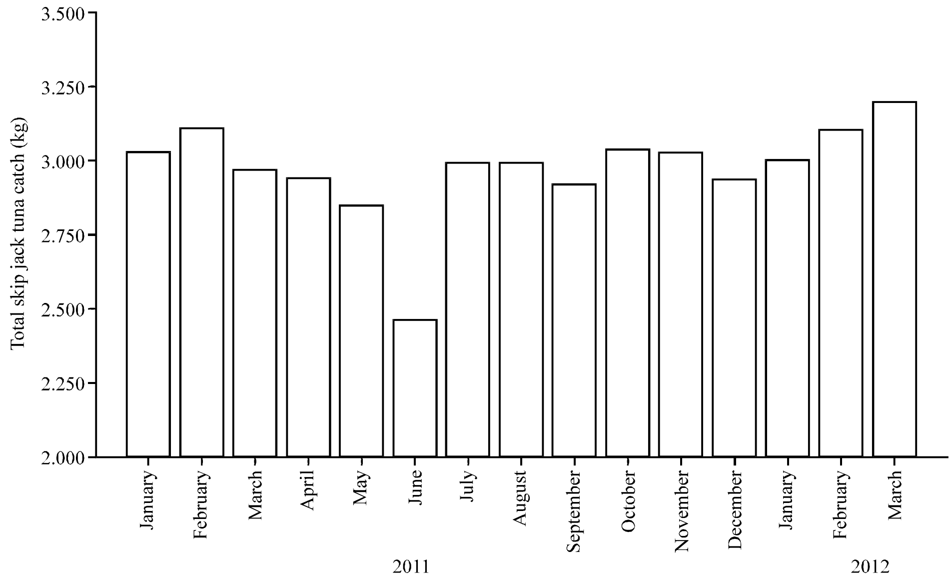

Fig. 5: Number of total skipjack tuna catch (kg) landed in Morotai Islands fishing port from January 2011-March 2012

During La Nina event in 2011, vertical struture of temperature within HE region is indicated by a shifting in farther North of isotherm depression (Fig. 4c) which is in good agreement with the bold presence of saline SPTW farther 6.5N (Fig. 4c).

Skipjack tuna catch: In Halmahera and its surroundings, particularly Morotai Island, consumption of tuna is high. Tuna catch is traditional fishing in many islands of the eastern Indonesia as it shown by the great number artisanal technics. The exploited areas were usually close to the shore. Skipjack (*Katsuwonus pelamis*) is common fish caught by local fisherman. The tuna can be caught throughout all years by the fishing season for Skipjack tuna occurred during April to May and from September to December.

Figure 5 shows Skipjack tuna catch during January 2011-March 2012 and indicates fluctuated catch with highest one in March 2012 (3191 kg) and lowest one in June 2011 (2460 kg).

DISCUSSION

As the region affected strongly by the monsoon system, the local wind of Asian-Australian monsoon will impact profoundly to HE. During boreal summer, strong forcing from New Guinea Coastal Current (NGCC) and New Guinea Coastal Under Current (NGCUC) becomes more intensive as HE size increases as shifts northwestward. In contrary, during boreal winter, the size of HE becomes much smaller as it is pushed southeastward by Mindanao Current (MC). Its eddy diameter also tends to decrease. On ENSO time-scale, when El Nino warm phase occurs, the current system in the Low Latitude Western Boundary Current (LLWBC) is decreased. Since the major flow from South Equatorial Current (SEC) is reduced by westerly wind burst, which exists normally on the onset of El Nino. Hence, HE shifts farther southeastward and its eddy diameter is much smaller but during La Nina, HE moves farther the northwest and eddy size is much bigger because the current system of LLWBC becomes more intensive due to much stronger South Equatorial Current (SEC) (Fig. 3).

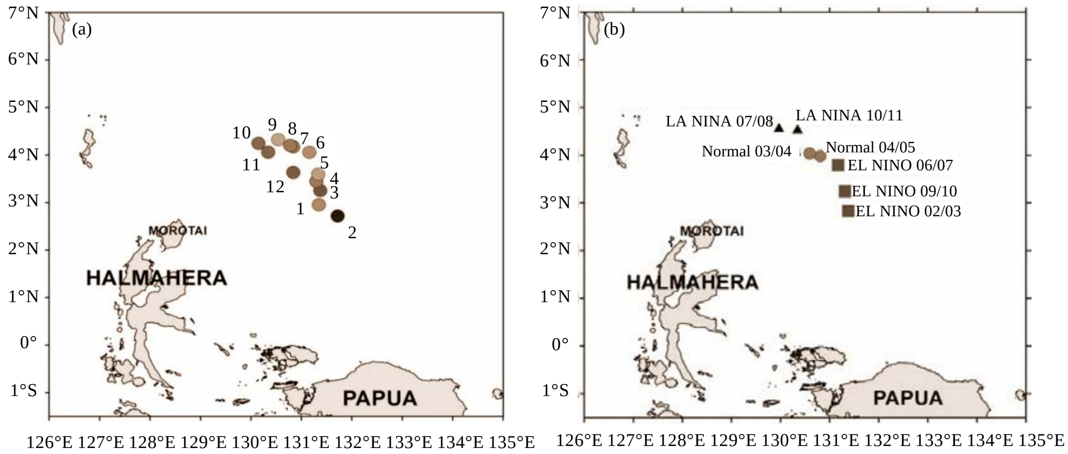

Fig. 6: Halmahera eddy movement pattern related to, (a) Seasonal (monsoon) and (b) Interannual (ENSO) time-scales variability

Different time frame analysis seems affectedly HE translation and circulation as shown from two different phase event of ENSO and season from two TOCS cruises in 2002 (El Nino year) and in 2011 (La Nina year). During El Nino 2002 cruise, HE shifted to the southeast more dominant but its increasing eddy diameter caused by summer monsoon. It was different during Normal year in 2008 cruise when HE shifted to the northwestward but its eddy diameter tends to decrease due to changing monsoon to be winter (Fig. 4). This result is in good agreement with (Kashino *et al.*, 2013), who have analyzed the cruises data during the El Nino 2002, normal year of 2008, southeast monsoon of 2011 and northwest monsoon 2013.

Their results showed similar patterns of translation and circulation with the present study. Schematic of HE northwest-southeastward shifts, related to seasonal (monsoon) and interannual (ENSO) time-scales variability (Fig. 6).

Response of subsurface temperature and salinity to the presence of clockwise circulation of HE is indicated by mixed layer depth deepens and pushes much deeper thermocline layer during boreal summer but a relatively shallow mixed layer depth is observed during boreal winter. Furthermore, as shown with isotherm contours, the center of HE is slightly tilted northward with increasing depth, which is consistent with results of Kashino *et al.* (2013). In the HE region, high saline SPSW thermocline water is dominant (Fig. 5). This water mass is transported by northwestward NGCCC along offshore northern Papua. In the northern boundary of HE near 5°N, a front of different water masses from southern and northern hemispheres is seen clearly, indicated by high vertical and horizontal gradient of temperature and salinity, as described by Kashino *et al.* (1996, 2007). Product of NP and SP water masses mixing is fed to be NECC water mass and part of them is recirculated within the outer ring of HE.

Figure 7 presents the relationship between HE translations and production of skipjack tuna catch, landed in Morotai islands or Northern tip of Halmahera island. We assumed that this area is within the center of HE. It is shown that when HE shifted farther the North, the catch production increased. In contrast, when HE moved southward, the catch production decreased, e.g., in June 2011 (Fig. 7).

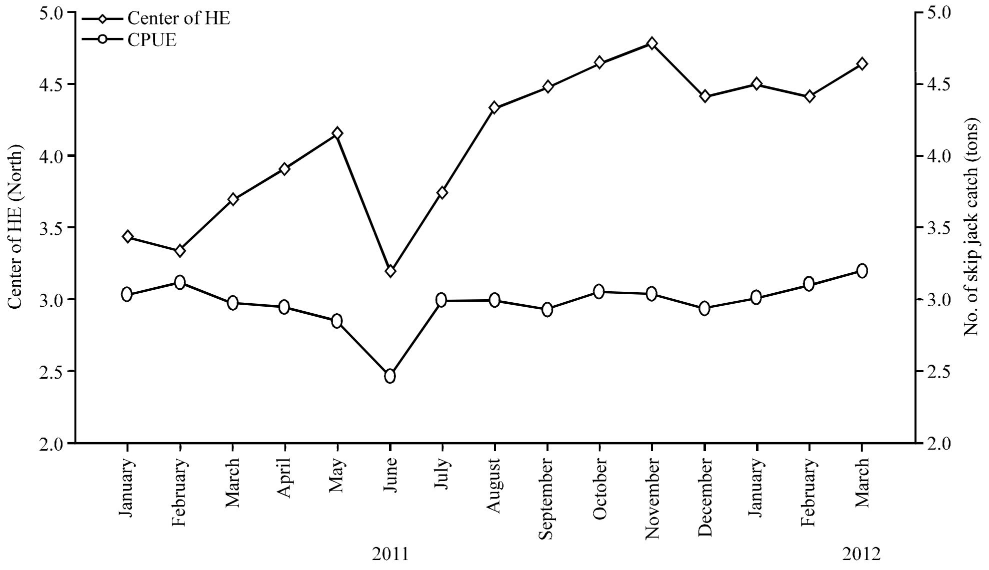

Fig. 7: Plot of meridional shifting of Halmahera Eddy with total skipjack tuna catch landed in Morotai islands, Indonesia during January 2011-March 2012

Correlation coefficient between the meridional shifting of HE and skipjack tuna catch production is near 45% rate due to lack of data availability but it gives prospecting result since the trend pattern having good similarity.

CONCLUSION

There are two-fold conclusions as follows:

- First, HE generates high chl-a ribbon in the northern rims of the eddy with averaged horizontal diameter of 520 km and averaged shifting along southeast-northwest axis of 392 km. HE is profoundly affected by seasonal and inter-annual time-scale variability in the western tropical Pacific waters. Seasonal time-scale has dominant influence in increasing (decreasing) eddy diameter during southeast (northwest) monsoon and inter-annual time scale has dominant influence in the southeast (northwest) translation during El Nino (La Nina) event. These HE pattern changes are also consistent with properties changes of subsurface temperature and salinity vertical profiles within the HE
- Secondly, meridional shifting of HE has similar pattern movement with skipjack tuna catch in the landing fish location around Morotai islands, Indonesia, near the center of HE. The northward (southward) movement from its center HE at 4N has relationship with increasing (decreasing) skipjack tuna catch. This implies that northwest monsoon and La Nina have better increasing skipjack tuna catch in the western tropical Pacific waters

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