The spatial current structure in the Indonesian Seas in November 2014, during The Expedition of Widya Nusantara (EWIN)

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Abstract

The spatial current patterns in the Indonesian seas were mapped based on a wide range of snapshot observations during the Expedition of Widya Nusantara (EWIN 2014) Leg 1 in November 2014. The current profiles were measured using the Shipboard Acoustic Doppler Current Profiler (SADCP) of the RV Baruna Jaya VIII. This study is aimed to reveal the current system in the Indonesian seas from observation. Remarkable current patterns of the Indonesian throughflow (ITF) were observed penetrating via the Mindanao Strait, southern Makassar Strait, and Lifamatola Passage, including its recirculation in the northern Maluku Sea and in the Sulawesi Sea. These results suggested that during the late Southeast Monsoon (SEM), the upper layer ITF is still significantly penetrating the Indonesian seas. The indication of anticyclonic and cyclonic circulations in the upper 50 m and lower 75 m, respectively, was also observed in the western Banda Sea.

Keywords: Indonesian seas, Indonesian throughflow (ITF), ADCP, current pattern

Abstrak

Struktur spasial arus di Perairan Indonesia pada bulan November 2014,selama Ekspedisi Widya Nusantara (EWIN). Pola arus spasial di perairan Indonesia dipetakan berdasarkan data observasi singkat jangkauan luas selama Ekspedisi Widya Nusantara (EWIN) Leg 1 pada bulan November tahun 2014. Profil arus diukur menggunakan alat pengukur arus akustik Doppler (SADCP) di Kapal Riset Baruna Jaya VIII. Kajian ini ditujukan untuk mengungkap pola arus di perairan Indonesia berdasarkan observasi. Beberapa struktur arus umumyang memperlihatkan penetrasi Arus lintas Indonesia (Arlindo) ditemukan dalam penelitian ini, yakni masukan di pintu masuk Arlindo, Selat Mindanao, Selat Makassar bagian selatan, dan Celah Lifamatola, termasuk resirkulasi di sebelah utara Laut Maluku dan Laut Sulawesi. Hasil-hasil ini mengindikasikan bahwa pada akhir periode Muson Tenggara, lapisan atas Arlindo masih signifikan memasuki perairan Indonesia.Indikasi terdapatnya pola sirkulasi antisiklon dan siklon berturut-turut pada lapisan atas hingga kedalaman 50 m dan 75 m juga terungkap di Laut Banda bagian barat.

Kata kunci: perairan Indonesia, Arus lintas Indonesia (Arlindo), ADCP, pola arus

Introduction

Indonesian region has been known as the maritime continent since it is believed that the waters surrounding this archipelago exist as connecting waters rather than separators. This region is located between Asia and Australia continents hence making this region has been exposed to the monsoonal winds system, i.e. the Northwest Monsoon (NWM) and the Southeast Monsoon (SEM) winds. Introduced firstly by Wyrtki (1961), the Pacific trade winds forced the warm equatorial Pacific watermass westward and creates a pressure gradient between the western tropical Pacific Ocean and the Indian Ocean, therefore triggering the throughflow namely the Indonesian throughflow (ITF).

Some studies quantified the ITF transport in several passages as follows. around 16.4 Sv (1 Sv = 1×10^6 m^3 s^{-1}) enters the Sulawesi Sea via the Mindanao Strait (Godfrey, 1989; Wei et al., 2016), 11.6 Sv enters the Makassar Strait (Gordon et al., 2008), 2.5 Sv enters the Seram Sea from the Maluku Sea via the Lifamatola passage below 1250 m yet in the upper layer, a reversing northward flow occurred (van Aken et al., 2009). The shallow ITF was also observed around 0.5 Sv via the Karimata Strait, entering the Java Sea from the South China Sea (Susanto et al., 2013).

In the western tropical Pacific region, two dominant forcing currents existed, i.e. the Mindanao Current (MC), appears as the southward bifurcated North Equatorial Current (NEC), and the New Guinea Coastal Currents (NGCC) in the northern coast of Papua Island, (Kashino et al., 1998, 2001, 2005, 2013). Only one-third throughflow via the Mindanao Strait enters the Makassar Strait, the remaining two-third is recirculated in the Sulawesi Sea and flowing back to the western Pacific Ocean (Masumoto et al., 1996), joining the portion of MC which flows eastward directly as the North Equatorial Counter Current (NECC) (Lukas et al., 1991). This recirculation might also be triggered by a west to east pressure gradient due to freshwater input from the South China Sea (SCS) via the Sibutu passage, especially during winter months (Wei et al., 2016).

Studying the spatio-temporal behavior of the ITF is important as this throughflow is part of global thermohaline circulations. The ITF watermass is distributed widely where around 89% and 11% enter the western boundary and eastern boundary of the Indian Ocean, respectively (Zhang et al., 2019). The ITF also controls the south Java upwelling strength in the eastern Java (Kuswardani et al., 2014). From climatic perspectives, ITF also controls salt and heat flux between the Pacific and Indian Oceans which affects the hydrological cycle in the tropical region (Petrick et al., 2019). From economical perspectives, for Pacific and Indian tropical rim countries, seawater properties variability and circulation patterns are connected to the fisheries aspect.

Still, a quantitative understanding of ITF characteristics will always be important for wide range users hence updating and monitoring its behavior is necessary. The analysis of a wide range direct current measurements using ADCP (Acoustic Doppler Current Profiler) measured during the Expedition of Widya Nusantara (EWIN) 2014 was presented in this study. This study is aimed to reveal the circulations in late of SEM period, in November. The mapping of spatial current patterns presented in this study is necessary to help understanding the ITF behavior simultaneously since the measurements were carried out in relatively the same period and covered a wide area.

Methods

A long track dataset of the Shipboard Acoustic Doppler Current Profiler (SADCP) 75 kHz *RD Instruments* measured on 16-28 November 2014 by RV Baruna Jaya VIII RCO-LIPI during the Expedition of Widya Nusantara (EWIN) 2014 Leg 1 was processed. The measurements were conducted using the transect method from 113.6^o E, 5.7^o S in the easternmost of the Java Sea to 125.0^o E, 1.8^o N, the Manado Bay waters (

Figure **1**).The current profiles were measured vertically up to 100 m depth and horizontally along the vessel's track. The profiles were recorded at several layers of bin (~depth) with 5 m vertical bin size (~vertical resolution). Due to systematic failure in the SADCP unit hence decreasesthe depth coverage of the measurements, here we processed the first 19 bins only. The first depth bin was 10 m and the lowest depth bin was 100 m. Horizontally, the SADCP *ping*frequency was set every 1 minute (known as ensemble in ADCP data processing), meaning that the current profile was captured every 185 to 247 m distances horizontally, by assuming the typical vessel's speed was 6 to 8 knots, respectively.

The measured currents were processed using the WINADCP data processing module to extract the zonal and meridional components. The spatio-temporal current measurements were processed following a method proposed by Candela et al. (1990) to eliminate the tide induced

variability from ADCP data. For this study, the vessel was moving with a relatively constant speed of 6-8 knots. The spatial Bartlett averaging of ~1 km were used to reduce local spatio-temporal variations that arise from local tidal variations. To inspect the spatial current variability, the current profile at 10 m, 25 m, 50 m, 75 m, and 100 m were mapped.

A dataset of surface drifter deployed in the Pacific Ocean was involved to further inspect the spatial circulations in the western tropical region closed to the observation area. The dataset was obtained from the Global Lagrangian Drifter Data of AOML/NOAA from 1986 to 2018 (http://www.aoml.noaa.gov/envids/gld/dirkrig/parttrk_spatial_temporal.php). The drifter tracks into two monsoonal periods, i.e. the NWM period, from December to May (DJFMAM), and the SEM period, from June to November (JJASON), were separated to identify any seasonal variability.
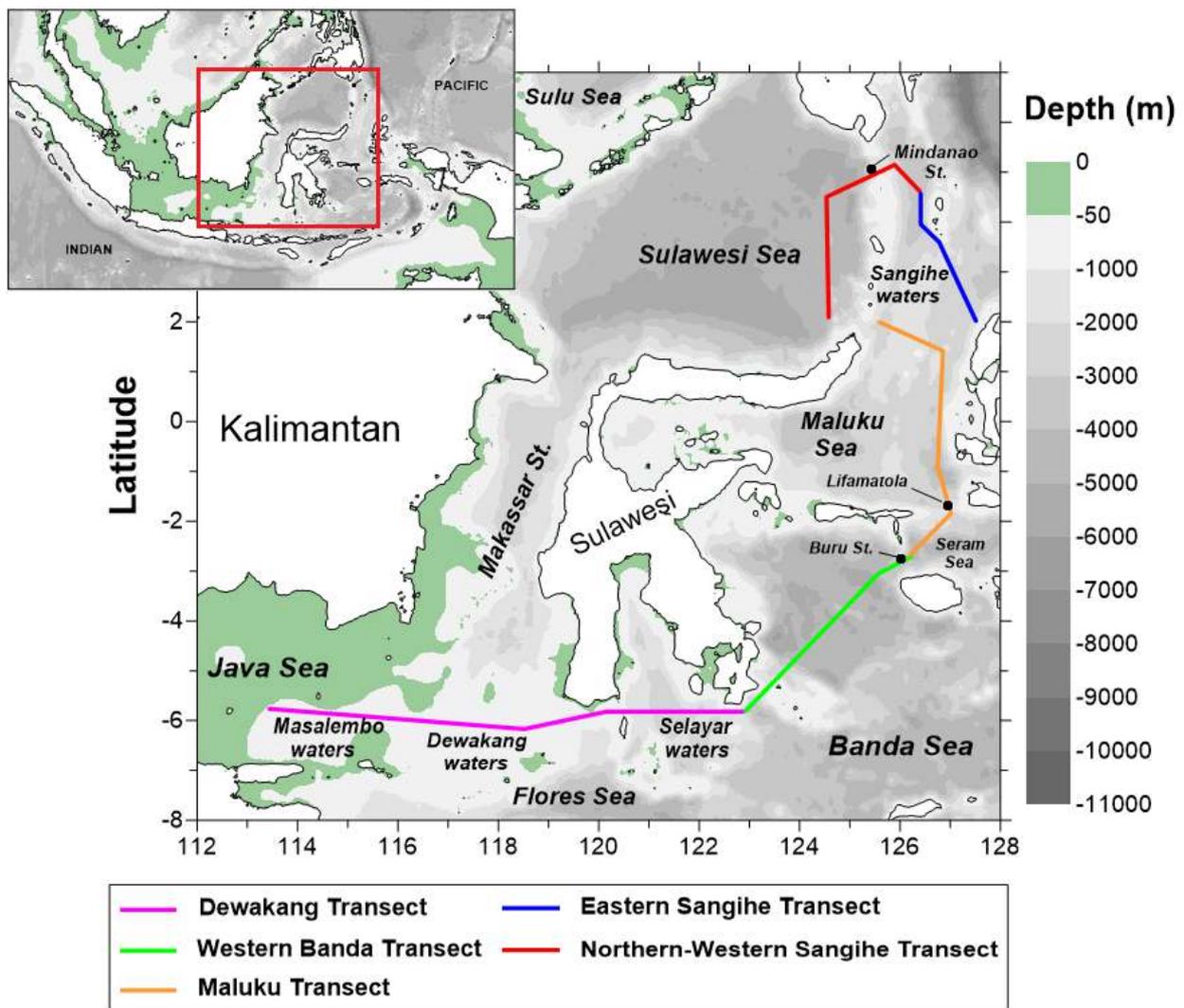

Figure 1. Map of Indonesian seas and surrounding waters, with topography inferred from ETOPO. The green area represents the shallow waters of less than 50 m depth. The transect of the Shipboard Acoustic Doppler Current Profiler (SADCP) is presented in different colors.

Gambar 1. Peta perairan Indonesia dan sekitarnya, beserta topografi berasal dari ETOPO. Area berwarna hijau adalah perairan dangkal dengan kedalaman kurang dari 50 m. Transek SADCP dipresentasikan dengan garis berwarna.

Results

Typical mean and maximum current speed for each transect is shown in Table 1. The descriptive

analysis of the spatial current patterns below refers to the track-classified map as shown in

Figure **1** and current pattern maps in Figure 2.

Table 1. Typical mean and range of current speed for each transect, from upper layer (10 m) to lower layer (50 m), during the Expedition of Widya Nusantara (EWIN) 2014 Leg 1, 16-28 November 2014. The values presented here are not the full depth mean and range values since each transect has different maximum depth. The values are estimated up to 50 m depth only so that comparable between transects.

Tabel 1. Tipikal rerata dan rentang kecepatan arus pada setiap transek, dari lapisan atas (10 m) hingga lapisan bawah (50 m), selama Ekspedisi Widya Nusantara (EWIN) 2014 Leg 1, 16-28 November 2014. Nilai yang ditampilkan di sini bukan merupakan rentang dan rerata nilai dari keseluruhan kedalaman karena setiap transek memiliki kedalaman yang bervariasi. Nilai tersebut diestimasi hingga kedalaman 50 m saja sehingga dapat dibandingkan nilainya antartransek.

Transect	Typical speed (m s^{-1})	
	Mean	Range
Dewakang	0.2	0.1-0.7
Western Banda	0.2	0.0-0.7
Maluku	0.4	0.1-1.1
Eastern Sangihe	0.5	0.1-1.0
Northern-Western Sangihe	0.5	0.1-1.5

The Dewakang transect

The eastward-southeastward currents were observed in Masalembo waters, <116° E, at 10 m and 25 m depth, with the typical mean speed of 0.2 m s^{-1} and a maximum speed of 0.4 m s^{-1} at 10 m and 0.2 m s^{-1} at 50 m (the maximum measured layer in the Masalembo waters). The southward current is intensified in the Dewakang waters, 116°-120° E, with the typical mean speed of 0.2 m s^{-1} and a maximum speed of 0.5 m s^{-1} at 10 m and 25 m, and 0.6 m s^{-1} at 50 m, 0.5 m s^{-1} at 75 m and 0.7 m s^{-1} at 100 m. Note that it is an open area, facing/exposed to the Makassar Strait directly in the north and the western Flores Sea and Lombok Strait in the south. In the Selayar waters (120°-123° E), the pattern differs spatially yet indicates eastward dominating component at 25, 50, 75, and 100 m. The typical mean speed is 0.2 m s^{-1} and a maximum speed of 0.4-0.5 m s^{-1} at all depths.

The western Banda transect

The northwestward currents in the northernmost of the transect and southward currents in the southernmost of the transect were observed at 10, 25, and 50 m, with the typical mean speed of 0.2 m s^{-1} and a maximum speed of 0.7 m s^{-1} at 10 m, and 0.5 m s^{-1} at 25 m, 50 m. A

counterclockwise direction spatially was indicated from the northernmost western Banda transect close to the Buru Strait, up to the southernmost transect. Below, at 75 m and 100 m, the current patterns oriented northeastward and are likely indicated a clockwise pattern, from the southernmost to the northernmost of the transect, with the typical mean speed of 0.2 m s^{-1} and a maximum speed of 0.5 m s^{-1}.

The Maluku transect

A relatively strong south-southeastward current in the Lifamatola passage with a typical maximum speed of 0.7-1.1 m s^{-1} was observedat 10, 25, and 50 m depth. Below, northward flow at 75 and 100 m are intensified gradually. In the central Maluku Sea (1° N-1° S), the southward current was observed at 10 and 25 m layers, with the typical mean speed of 0.3-0.4 m s^{-1}, the maximum speed of 0.6-0.7 m s^{-1}, and reversed northward current at 50, 75, and 100 m with the maximum speed of 0.6, 0.8 and 0.5 m s^{-1}, respectively and typical mean speed of 0.2-0.3 m s^{-1}. In the northernmost Maluku Sea (1°-2° N), eastward-southeastward currents were observed at 10 m and 25 m, with the typical mean speed of 0.4 m s^{-1} and a maximum speed of 0.7 m s^{-1}; and clear re-orientation to eastward-northeastward occurred

at 50, 75 and 100 m with the typical maximum speed of 0.6, 0.4 and 0.4 m s^{-1}, respectively; and the mean speed of 0.3 m s^{-1}. Note that all mean values descibed in the text are averaged from the whole measured layers.

The Sangihe transects

Persistent northeastward currents were observed for all depths in the eastern Sangihe transect (plotted in blue in Figure 2), with the typical mean speed of 0.4-0.5 m s^{-1} and the maximum speed of 0.9 m s^{-1} at 10, 25, 50 and 75 m; and 1.0 m s^{-1} at 100 m. In the northern-western Sangihe transect (plotted in red in Figure 2), which includes the Mindanao Strait here, the southward currents with the typical mean speed of 0.4-0.5 m s^{-1} and a maximum speed of 0.8-1.1 m s^{-1} were observed at 125.8^{o}-126° E (the eastern Mindanao Strait). In the middle of the strait (124.7^{o}-125.8^{o} E), the westward-southwestward currents were observed with the typical mean speed of 0.6 m s^{-1} at 10 m and 25 m, 0.7 m s^{-1} at 50 m, 0.9 m s^{-1} at 75 m and 1.0 m s^{-1} at 100 m; and the maximum speed of 1.2-1.4 m s^{-1}. In the western Sangihe waters (transect along 124.6^{o} E), the southwestward currents were observed at 3°-4° N, with the typical mean speed of 0.4-0.5 m s^{-1} and a maximum speed of 0.8 m s^{-1} at 10 m, 0.9 m s^{-1} at 25 m, 1.0 m s^{-1} at 50 m, 1.1 m s^{-1} at 75 m and 1.0 m s^{-1} at 100 m. Yet, at 2°-3° N, the reversed eastward currents were observed, with the typical mean speed of 0.3-0.4 m s^{-1} and maximum speed of 0.5 m s^{-1} at 10 m, 0.6 m s^{-1} at 25 and 50 m; and 0.8 m s^{-1} at 75 and 100 m.
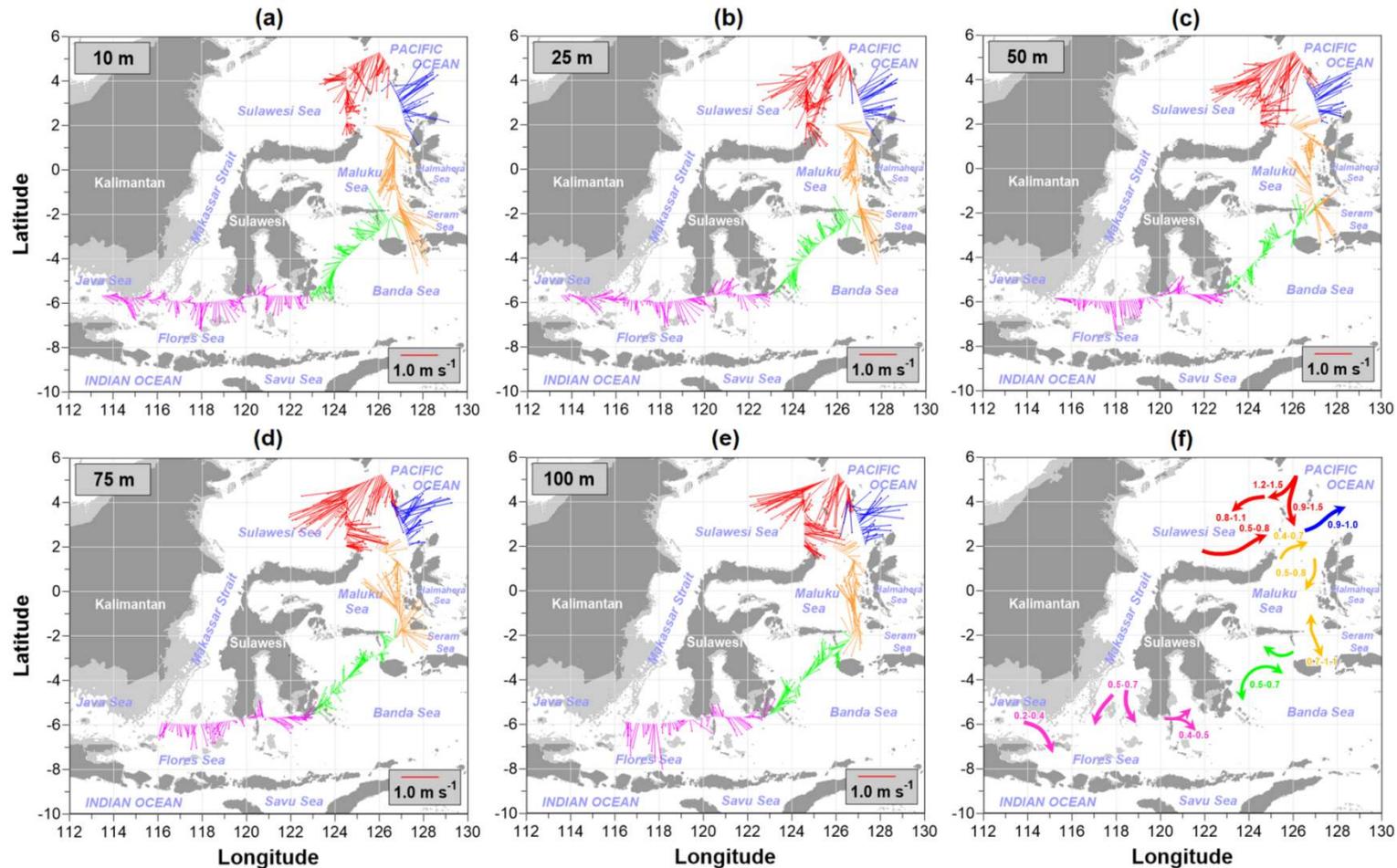
Figure 2. Spatial currents variability in the Indonesian seas measured on 16-28 November 2014 at: (a) 10 m, (b) 25 m, (c) 50 m, (d) 75 m and (e) 100 m. (f) Mean circulation sketch deduced from the observed currents with the typical range of maximum speed is indicated. Different colors represent classified areas which refer to Figure 1, to ease the analysis. The topography provided by ETOPO, with 50 m isobaths is presented in light gray.

Gambar 2. Variabilitas spasial arus di perairan Indonesia yang diukur pada tanggal 16-28 November 2014 pada kedalaman: (a) 10 m, (b) 25 m, (c) 50 m, (d) 75 m, (e) 100 m.(f) Sketsa sirkulasi yang dideduksi dari arus-arus terukur, dengan tipikal nilai maksimum. Perwarnaan plot yang berbeda merepresentasikan klasifikasi area yang merujuk ke Gambar 1, untuk memudahkan analisis.Topografi diperoleh dari ETOPO dengan kedalaman 50 m ditampilkan dengan warna abu-abu muda.

Discussion

In the Dewakang transect, the eastward current in the Masalembo waters up to 25 m depth indicates the influence of the Java Sea current system, with deflected southeastward current, which is likely due to pressure gradient between the Java-Flores Seas with the Indian Ocean via the Lombok Strait. The mechanisms responsible for this patternin the Selayar waters can not be characterized precisely on this cruise. It could be tidal current combined with offshore mean current due to upwelling event. Note that the southern Sulawesi waters are exposed to upwelling event during the SEM period(Inaku, 2017; Utama et al., 2017).The time series current measurements are needed to be able to decompose the measured currents into its contributors, i.e. the tidal current and the mean current.

In the western Banda transect, our results indicated the existence of two different eddies system working in the Banda Sea: the counterclockwise pattern in the upper 50 m and the clockwise pattern at 75 and 100 m. This pattern is seemingly following simulation studies in the Banda Sea which show that during the SEM period, the circulation pattern in the upper layer (<500 m) is anticyclonic, with the contribution also from the Coriolis force working in the western Banda Sea; below which, the pattern is cyclonic (Liang et al., 2019; Zhu et al., 2019). However, observational-based finding in this study suggests that the cyclonic pattern was observed shallower. Note that in this study observations were conducted during late of SEM, which may reduce the thickness of the upper eddy.

In the Maluku transect, the strong southward current directing to the Seram Sea from the Maluku Sea via the Lifamatola passage is not surprising. It is likely triggered by the pressure gradient between the Maluku Sea and the Seram Sea. Since most of previous studies (see Tan et al., 2020; van Aken et al., 2009) has been focused on the deep overflow in this passage,therefore comparing those studies with the observations in this study is not possible. The Lifamatola throughflow plays an important role as it is responsible for enhancing the upwelling event in the Banda Sea via Ekman pumping mechanism (Zhu et al., 2019).

In the Sangihe transects, the observation in this study indicated several current systems in the western tropical Pacific Ocean, i.e. the southward MC, the westward deflected MC which enters the Sulawesi Sea as the origin of the ITF, and the eastward retroflected back current from the Sulawesi and Maluku Seas towards the Pacific Ocean. These results strengthen previous studies (Kashino et al., 2001, 2005, 2013; Yuan et al., 2018). Besides, the year 2014 was categorized as a weak El Niño year (NOAA, 2014). During El Niño (La Niña) years, the deep (shallow) ITF in the Mindanao and Makassar Straits are maximum (minimum) in the deep (shallow) layers (Jiang et al., 2019). This 2014 ENSO events might be related to the very strong Mindanao Strait currents (up to $\sim$2 m s^{-1}) (see Figure 2, the red plots and Figure 3, the MC).

Historical drifter buoy dataset from 1986 to 2018 indicated some regular circulations exist in the western Pacific Ocean. In this study no significant difference pattern between the NWM and SEM patterns except more tracks during the SEM period in the northern Papua waters due to intensified NGCC during this period from the south equatorial Pacific Ocean. Figure 3 shows the plot of surface drifter buoys from 1986 to 2018 deployed in the Pacific Ocean, which indicate the existence of common circulations in this region: the NEC at the higher latitude of 8° N, the MC along the eastern coasts of the Philippines, as the southward retroflected NEC, the Mindanao Strait-Sulawesi Sea current as the westward retroflected MC, and the NECC(North Equatorial Counter Current) as the eastward retroflected MC. Note that the MC, as well as the NEC, occurred as the response to wind forcing in the tropical Pacific Ocean and the characteristic of ITF via the Mindanao Strait is similar to that of the Makassar Strait (Ren et al., 2020) hence the variability of the Makassar Strait throughflow is also controlled by the Mindanao-Sulawesi throughflow. This explains why strong southward currents in the southern Makassar Strait (the Dewakang waters) from the SADCP measurements were observed. The existence of recirculation in the Sulawesi Sea and the northern Maluku Sea back to the Pacific Ocean (eastern Sangihe waters) in the drifter paths were also detected. These features are also in line with the spatial current profiles gained from observation in this study.
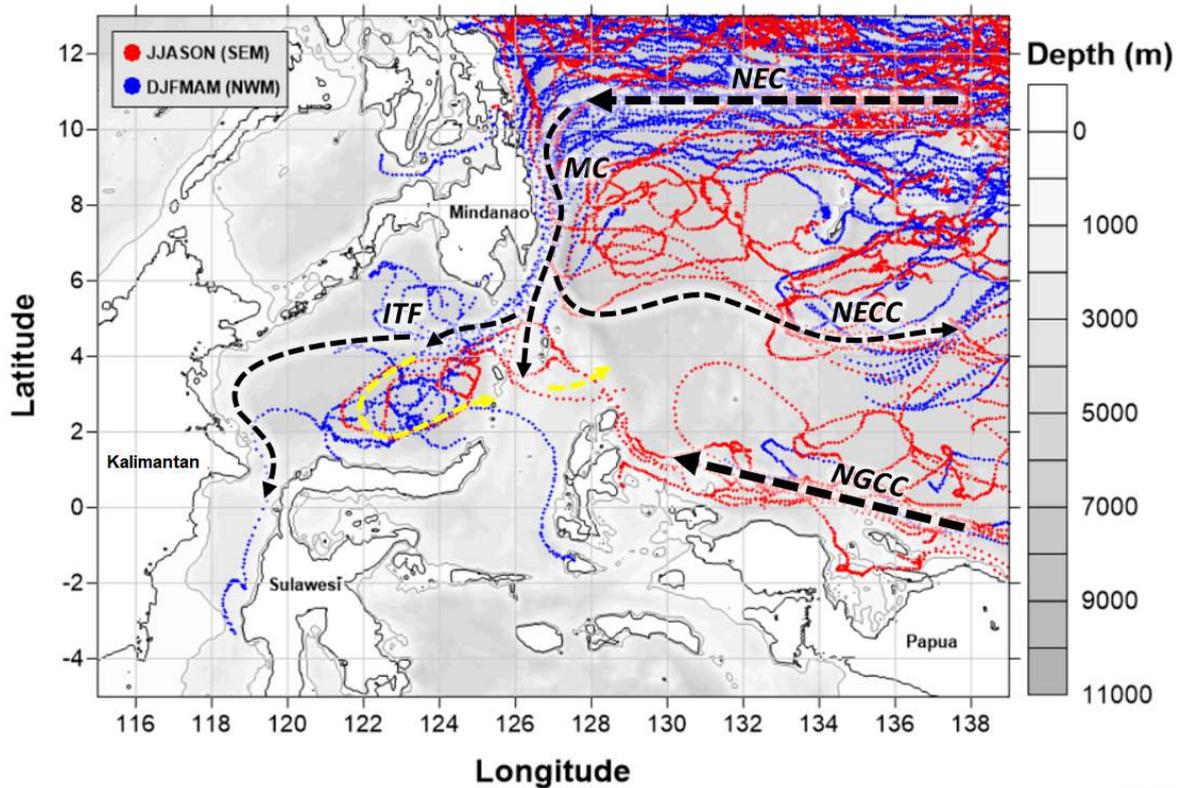
Figure 3 Plot of Lagrangian surface drifters deployed in the Pacific Ocean obtained from the Global Lagrangian Drifter Data of AOML/NOAA, from 1986 to 2018. The red plots represent Southeast Monsoon (SEM) months period (June to November, JJASON) and Northwest Monsoon (NWM) month period (December to May, DJFMAM), respectively. The dashed arrows represent general circulations, sketched basedon the appearance of the tracks: North Equatorial Current (NEC), Mindanao Current (MC), Indonesian Throughflow (ITF), North Equatorial Counter Current (NECC) and New Guinea Coastal Current (NGCC). The yellow dashed arrows represent the retroflected ITF, back to the Pacific Ocean. The topography depth is provided by ETOPO, with grey topography contours represent 300 m isobaths.

Gambar 3 Plot Lagrangian *drifter* permukaan di Samudera Pasifik yang diperoleh dari data drifter Lagrangian AOML/NOAA, dari tahun 1986 hingga 2018. Plot merah dan biru berturut-turut adalah plot untuk bulan-bulan Muson Tenggara (Juni hingga November) dan bulan-bulan Muson Barat Laut (Desember hingga Mei). Tanda panah garis putus-putus menyatakan sirkulasi umum yang disketsakan dari penampakan lintasan drifter: Arus Ekuator Utara (NEC), Arus Mindanao (MC), Arus lintas Indonesia (ITF), Arus Balik Utara Ekuator (NECC) dan Arus Pantai Nugini (NGCC). Tanda panah kuning adalah retrofleksi ITF, kembali ke Samudera Pasifik. Topografi diperoleh dari ETOPO, dengan kontur abu-abu adalah kedalaman 300 m.

Conclusions

Direct current measurements up to 100 m depth conducted during the Expedition of Widya Nusantara (EWIN) Leg 1 in November 2014 highlighted a well-known circulation pattern in the Indonesian seas as has been indicated by previous models and observational-based studies, i.e. the strong throughflow in the ITF entrance passage, the recirculation in the Sulawesi Sea and in the northern Maluku Sea, the southward flow ITF from the Makassar Strait in the Dewakang waters and strong Lifamatola throughflow. This study also proved the existence of cyclonic and anticyclonic circulations in the Banda Sea. In the future, along with the simulations study, the wide range snapshot observation willalso be a fruitful method to give an insight into arranging a well-managed research exploration, for example where an advanced instruments should be put to monitor and/or explore new phenomena. Our study indicated that putting mooring instruments in the Banda Sea is recommended to reveal in detail the circulations in this area. Thus far, the Banda Sea is the most unexplored waters in the Indonesian territorial waters.

Acknowledgment

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