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The distribution of radiocesium in the Indian ocean and its relation to the exit passage of the Indonesian Throughflow

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HIGHLIGHTS

- Potential sources of anthropogenic radiocesium from North Pacific Sea.
- Indonesian Throughflow (ITF) can brings water mass from the Pacific Ocean to the Indian Ocean.
- The Southern Bali Waters and the Southern Lombok waters are exit passages of ITF.
- Marine monitoring of radiocesium in the exit passage of Indonesian Throughflow (ITF).

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ABSTRACT

The objective of this study was to determine the presence of radiocesium (^{134}Cs and ^{137}Cs) at the monitoring sites and to link its presence to the characteristics and mass water dynamics at the exit of the Indonesian Throughflow (ITF). The main sources of radiocesium are from human activities in the North Pacific Sea, such as from global fallout and release from the Fukushima Dai-ichi Nuclear Power Plant (FDNPP) reactor, and are potentially brought to Indonesian waters through the Indonesian Throughflow mechanism. Sea water samples were collected from the surface, thermocline, and deep layers during the expedition. The concentration of ^{137}Cs on the surface was between 0.042–1.003 Bq m^{-3}, the concentration range in the thermocline layer was 0.008–0.795 Bq m^{-3}, and the concentration in the deep layer was 0.046–0.680 Bq m^{-3}. The ^{134}Cs concentration was below the detection limit, which indicates that the ^{137}Cs comes from global fallout. In this research, the measurement of oceanographic parameters was also conducted, and the results showed that temperatures were in the range of 4.982–27.45 ° C, salinity was in the range of 34.232–34.979 PSU, and the density was between 22.0979–27.4028 kg m^{-3}. The salinity profile indicates that the eastern part had a lower salinity level than the western part. The Pacific Equatorial Water Mass was found to be the most dominant in the ITF. Furthermore, these oceanographic data were combined with ^{137}Cs data to determine the distribution pattern of ^{137}Cs both horizontally and vertically in the exit passage of the ITF.

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1. Introduction

On March 11, 2011, an accident occurred in the Fukushima Dai-ichi Nuclear Power Plant (FDNPP) reactor, which was caused by an earthquake with a magnitude of 9.0 on the Richter scale (Honda et al., 2012; Inoue et al., 2012a; Yamamoto et al., 2014). Approximately 10^{19} Bq of radionuclides were released into the environment (Sakaguchi et al., 2012), and approximately 10^{17} Bqs of ^{137}Cs, ^{134}Cs and ^{131}I spread into the global aquatic environment (Chino et al., 2011). The total amount of ^{137}Cs released directly into marine waters was estimated to be 2.7×10^{16} Bq (Bailly du Bois et al., 2012). Tsumune et al. (2011) estimated that 1.60×10^{17} Bq ^{131}I and 1.5×10^{16} Bq ^{137}Cs were released into the Pacific Ocean. Steinhauser et al. (2014) estimated that more than 80% of the ^{137}Cs released into the atmosphere is deposited in the Pacific Ocean. The potential for these radioactive elements to enter Indonesian waters is relatively high due to the Indonesian Throughflow system (ITF).

The Indonesian Throughflow (ITF) is a system of water mass circulation from the Pacific Ocean to the Indian Ocean through Indonesian waters caused by the sea level difference of both oceans. The Pacific water mass consists of the North and South Pacific water masses (Gordon et al., 2010; Sprintall et al., 2009). The ITF

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transports Pacific Ocean waters into Indonesian waters through two paths. The West Line is driven by the Mindanao Current (Mindanao Current) through the Sulawesi Sea to the Makassar Strait, the Flores Sea, and the Banda Sea. The East Line is driven by the Papua Coast Flow (New Guinea Coastal Current) through the Maluku Sea and the Halmahera Sea to the Banda Sea. This water mass enters the Indian Ocean through several straits (Gordon et al., 2010; Ilahude and Gordon, 1996). Well-known exit passages are the Lombok Strait, the Timor Strait, the Ombai Strait, the Sumba Strait, and the Sawu Strait (Sprintall et al., 2009).

According to Morey et al. (1999), the ITF water mass originates from North Pacific (92%) and South Pacific waters (8%). Meanwhile, 80% of ITF's water mass is channeled through the Makassar Strait (Gordon, 2005; Tillinger, 2011). The volume of ITF water mass flow from the North Pacific transported through the Makassar Strait is 11.8 Sv (1 Sv = 10^6 m^3 s^{-1}) and through the Karimata Strait is 1.4 Sv, while the water mass flow rate in the South Pacific ITF transported via the Lifamatola Strait is 2.7 Sv. The water mass is then transported out of Indonesian waters to the Indian Ocean through the Lombok Strait, the Ombai Strait, and the Timor Trajectory, with volumes of 2.6 Sv, 4.9 Sv and 7.5 Sv, respectively (Gordon et al., 2010; Tillinger, 2011). The ITF water mass trajectory is directly related to the Indian Ocean, whose water dynamics are influenced by the monsoon wind system (Pranowo et al., 2016). The ITF has a maximum value during the Southeast Monsoon, where the flow of currents is in the direction of ITF transports – from the southeast to the northwest – thus amplifying surface currents (Atmadipoera et al., 2009). In this season, the South Waters of Java-Nusa Tenggara are affected by the ITF water mass and experience a decrease in surface temperature from 27.5 °C to 25 °C due to upwelling, the widening the axis of the *Arus Khatulistiwa Selatan* (AKS) and the loss of *Arus Pantai Jawa* (APJ) (Wilopo, 2005). The dynamics in the Indian waters become increasingly complex when phenomena such as the Indian Ocean Dipole, eddies, El Nino Southern Oscillation (ENSO), and Kelvin waves are also considered (Gordon, 2005). These complex dynamics affect the water masses the ITF brings to this location.

The water mass from the Pacific Ocean that contains radiocesium can enter Indonesian waters through the North Equatorial Current (NEC). According to You et al. (2005), this current carries water from the North Pacific Subtropical Water Mass (NPSW, salinity 34.5–34.8 PSU, density 24.5 kg m^{-3}, depth 130 m) and the North Pacific Central Water Mass (NPCW, density 34.2 ppt, 26 kg m^{-3}, depth 300–400 m) into the Sulawesi Sea following the ITF cycle. NPSW is formed by the North Pacific subtropical front and is transported first by recirculation of the Kuroshio Current and then transported by the NEC and the MC to the Sulawesi/ITF Sea. NPCW is formed by water subduction during late winter at the surface along the southern Subarctic-Tropical Frontal Zone (SATFZ) of the North Pacific, located at 40° N. This water mass is transported by the North Pacific Stream and then transported to the Sulawesi/ITF sea by the NEC and the MC. Meanwhile, Ilahude and Gordon (1996) mentioned that the Pacific Ocean water masses brought by the NEC to Indonesian waters are NPSW (salinity 34.6 PSU, depth 80–200 m) and the North Pacific Intermediate Water Mass (NPIW, salinity 34.45 PSU, depth 250–400 m).

Radiocesium is a fission product, composed of ^{134}Cs and ^{137}Cs and is of particular concern to the aquatic environment, due to its long half-life, especially of ^{137}Cs (half-life of 30.2 years) (Bailly du Bois et al., 2012). It also acts conservatively and is soluble in seawater, so its spread in the ocean is strongly influenced by the physical process of mixing and diffusion (Kawamura et al., 2011). To anticipate the possible entry of radionuclide contaminants to Indonesian waters, ^{137}Cs has been monitored in various areas through the national radioactive marine monitoring program, which includes monitoring in several Indonesian coastal waters and of several marine biota species (Suseno et al., 2018; Suseno and Prihatiningsih, 2014). This monitoring includes deep-sea monitoring off the west coast of Sumatra-Indian Ocean (Suseno et al., 2015), and monitoring in the ITF inlet (Suseno et al., 2017a,b) and the ITF outlet (Suseno and Wahono, 2018). The results from the above initiatives have not yet described the behavior of radiocesium across several layers of water due to the lack of data at the ITF exit passage.

This research was conducted from the Southern Waters of Java to the Southern Waters of Lombok, where the Indian Ocean greatly influences the water mass at the ITF exit passage. This region is part of Fisheries Management Area (WPP)-573, in accordance with the decision of the Minister of Marine Affairs and Fisheries of the Republic of Indonesia (KEP.45/MEN/2011). The WPP-573 is a major fishing area and one of the national fisheries gateways, so information about the presence of radiocesium is vital for maintaining food safety. Sampling of surface water, the thermocline layer, and deeper layers was conducted to investigate the radiocesium concentration. The subsequent measurement of oceanographic parameters combined with ^{137}Cs presence data was also carried out to determine the distribution pattern of ^{137}Cs in the ITF exit passage both horizontally and vertically.

2. Methods

Water sampling (surface, thermocline, and deep layers) was carried out to enable radiocesium analysis (^{137}Cs and ^{134}Cs), and measurement of water mass properties (temperature, salinity) was conducted to enable oceanographic analysis. Sixteen water samples were taken at oceanographic stations on the RV Baruna Jaya IV from 22 September to 6 October 2015. Research sites were located in the southern water of Java to Lombok, especially around the ITF exit passage, within coordinates of 06°59′08″-10°06′74″S and 105°49′36″-116°23′53″E (Fig. 1).

Water samples were collected using buckets and Niskin bottles combined with CTD equipment. Seawater samples taken from each sampling station measured approximately 150 L, we combined water sample from Niskin bottles until reach 150 L for each depth sampling. For the determination of radiocesium, these water samples were prepared according to the procedures described by Suseno and Prihatiningsih (2014), with some modifications. Ten g of copper (II) nitrate salt was added to the water samples and stirred until homogeneous. Ten g of potassium hexacyanoferrate (II) trihydrate was then added and stirred again for approximately 1 h until forming a uniform brownish red solution. The water samples were left for 24 h to allow for settling. The precipitates containing ^{137}Cs were dried and placed in a plastic container before gamma counting. Radiocesium (^{137}Cs and ^{134}Cs) was measured using gamma counting at photopeaks of 661 keV and 953.8 keV, respectively. The measurement time for each sample was 259,200–345,600 s. Three HPGe detectors were used, with counting efficiencies of 20%–25% and FWHM (Full Width Half Maximum) of 1.8 keV for a peak of 1332 keV of ^{60}Co. The gamma spectrometers used were Canberra type GX2018, Canberra type GC2020, and Ortex type GMX 25P4-76. The method covered detector calibration and determination of detector counting efficiency. Following these steps, Samples analysis were conducted by cumulative counts of both background and samples. Determination of radiocesium concentration in seawater is critical to reliable assessment of marine radioactivity. Quality assurance (QA) is vital for comparable and harmonized data generation. The QA program consists of several steps such as selection and validation of analytical methodology, resources used for the analysis, laboratory operations for sample handling and analysis, quality control, monitoring, and auditing. Certified Reference Materials (CRM IAEA 381) were used for evaluation of accuracy.

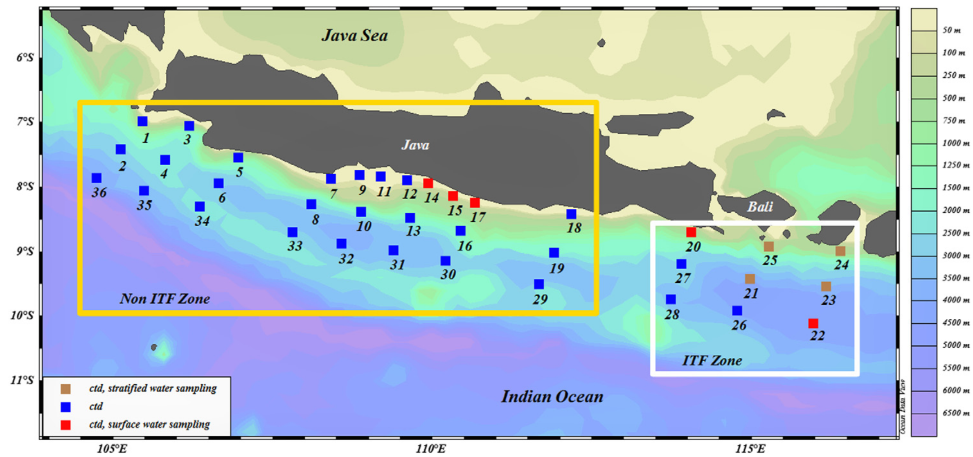

Fig. 1. Research stations.

Table 1
Grouping the research stations.

Location	Area	Station
Transect 1	Offshore	36, 35, 34, 33, 32, 31, 30, 29, 28, 26, 22
Transect 2	Transition	2, 4, 6, 8, 10, 13, 16, 19, 27, 21, 23
Transect 3	Coastal	1, 3, 5, 7, 9, 11, 12, 14, 15, 17, 18, 20, 25, 24

Table 2
The results of measuring the properties of water masses in the two zones.

Zona	Location	Temperature (°C)		Temperature (°C)	
		Max	Min	Max	Min
ITF Zona (Southern Lombok)	Transect 1	37.39	4.99	34.85	34.28
	Transect 2	26.58	4.98	34.83	34.23
	Transect 3	25.89	9.08	34.78	34.36
Non ITF Zona (Southern Jawa)	Transect 1	27.45	5.20	34.98	34.32
	Transect 2	27.09	5.25	34.94	34.34
	Transect 3	26.57	7.91	34.93	34.41

Oceanographic data from the CTD SBE (Sea-Bird Electronic) 9 Plus acquisition was processed using Ocean Data View Version 4 (2016). The calculation to transform conductivity into salinity, pressure into depths, the calculation of density values, and the value of potential temperature (Θ) used equations listed in Thermodynamic Equation Of Seawater (TEOS)-10 (McDougall et al., 2010). Prior to the profile creation stage with ODV(Ocean Data View) it is important to perform QC (Quality Control) on the acquired data. This activity was aimed at eliminating spikes, anomalies, or removing commonly found errors.

Analysis of the water mass layer structure used the temperature decrease gradient approach. The thermocline layer has a temperature gradient of 0.05 °C m^{-1} (Bureau of Technical Supervision of the People's Republic of China , 1992). The water mass above the thermocline layer is called the homogeneous water mass/mixed layer, and the water mass below the thermocline is called the deep water mass. The data analysis of the water mass physical properties used to infer the origin of water mass is generally distinguished in two regions: the territorial waters of South Java, which are categorized as a water area that does not receive the direct influence of the ITF water mass from its exit (Non ITF Zone), and those waters which are still strongly influenced by the mass of ITF water from the exit of the Lombok Strait and other Eastern straits (ITF Zone). To present the cross-sectional distribution of the water mass properties at the research site, it is necessary to group the research stations into three transects as listed in Table 1.

3. Results and discussion

A large quantity of radiocesium released from the Fukushima Dai-ichi Nuclear Power Plant (FDNPP) in 2011 has entered the Pacific Ocean directly or through atmospheric precipitation (Bailly du Bois et al., 2012; Steinhauser et al., 2014). It then has spread to the world ocean, including Indonesian waters through the ITF mechanism. One of the entrances is the Sulawesi Sea, which connects to the Makassar Strait; water passing through these straits then exits to the Indian Ocean through the Bali and Lombok Straits. Water masses in the two zones show higher offshore sea surface temperature and salinity (Table 2). The vertical distribution profile of temperature, salinity, and density in both zones shows a similar pattern and does not show an anomaly in the linear path (Fig. 2). The study was conducted in September–October 2015 or during the second transitional season, the transition from East to West Season. The southeast monsoon still shows its influence, even though it is starting to weaken.

The vertical distribution of temperature indicates that the thermocline layer was uplifted to a depth of less than 50 m. In the Southern Waters of Java, the thermocline layer has an upper limit of 11 m–31 m and a lower limit of 133 m–136 m, and typically has a thickness of 122 m–125 m. The average temperature gradient in this zone is 0.091 °C m^{-1}. In the Southern Waters of Lombok, the thermocline layer has an upper limit of 4 m–20 m and a lower limit of 77 m–169 m and is typically 73 m–149 m thick. The average temperature gradient in the ITF zone is 0.09 °C/m. Based on these data, the distribution of the thermocline layer is similar in both zones, and the thickness of thermocline layer is greater offshore. The difference that can be noted is that the thickness and upper and lower limits of the thermocline layer in the Southern Lombok Waters are shallower compared to the Southern Java Waters. This condition is more due to the influence of the Southeast Monsoon Winds and the Southern Equatorial Current (SEC) transporting surface waters to the west and away from shore. This condition is also reinforced by the ITF transport which is also to the west. A special note is for research station 24, which is strongly influenced by the Alas Strait current. Here, the water tends to be more homogeneous due to narrow straits causing the current to move rapidly, thereby pushing the thermocline layer to greater depths at this station (Fig. 3.b3.)

Cesium 137 (^{137}Cs) was detected at all research stations in the waters associated with the ITF exit passage, both in the Southern Waters of Lombok and in Java. The existence of ^{137}Cs was not only found on the surface layer but also in the thermocline and deep layers (Table 2). In contrast, ^{134}Cs was under the detection limit. The presence of ^{137}Cs shows that the contaminated Pacific

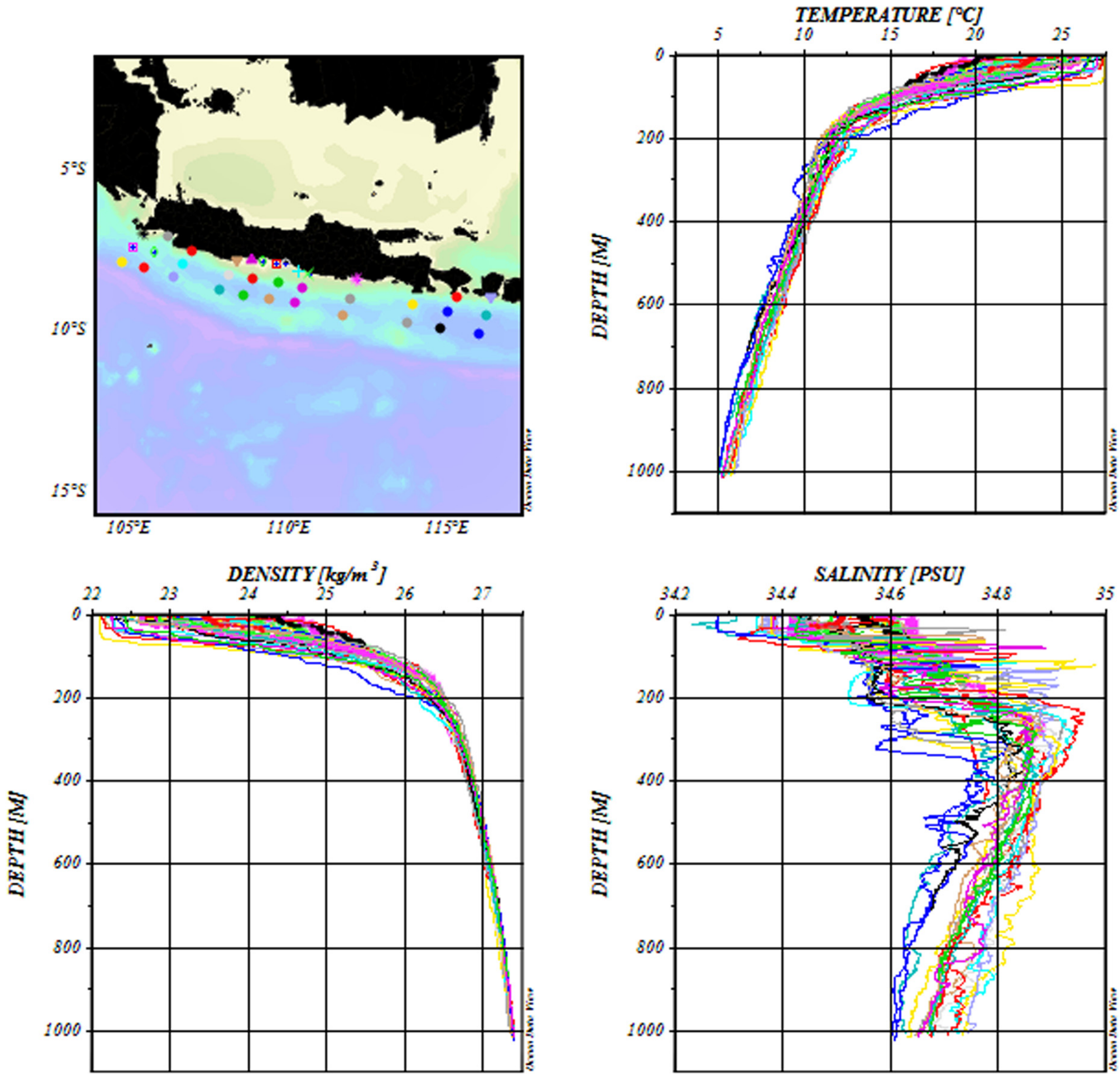

Fig. 2. Profile temperature, salinity and density.

water mass reaches the Indian Ocean through the ITF exit passage, especially in the Southern Waters of Lombok and Java (see Table 3).

Based on the plotting of temperatures and salinity data that used ODV software, we get a T–S diagram that shows the Pacific water mass in both zones is from the Northern and Southern Pacific Oceans. Water masses from the North Pacific include the Pacific Equatorial Water (PEW), the Eastern North Pacific Water (ENPW), the Western North Pacific Water (WNPW), while water masses from the South Pacific include the Southern Pacific Intermediate Water (SPIW), the Eastern South Pacific Water (ESPW), and the Western South Pacific Water (WSPW). The influence of the Pacific water mass could be seen more clearly on the Southern Waters of Lombok than on the Southern Waters of Java. The results of the analyses show that the waters of the ITF zone were from the Southern and Northern Pacific Ocean. The water masses of the Eastern South Pacific Water was found to be dominant at a depth of 200–700 m, with typical temperatures ranging from 9 to 16 °C and salinity values at 34.3–35.10 PSU. The other dominant water mass found was the Western South Pacific Water, at a depth of 200–800 m with temperatures ranging from 7 to 16 °C and salinity ranging from 34.5 to 35.5 PSU. Meanwhile, the water mass of the Northern Pacific Ocean was found in the ITF zone, and the most dominant water mass in the ITF zone was the Pacific Equatorial Water. This water mass was characterized by temperature values of 6–16 °C and salinity 34.5–35.2 PSU and was found at a depth of 200–800 m. These results are in line with previous research results (Ilahude and Gordon, 1996; Sprintall et al., 2009). The types of water masses in the ITF Zone are also found in the Southern Waters of Java. Previous research by Atmadipoera et al. (2009) mentions that the Pacific water mass is found in the Waters of Southern Java. The influence of the Indian Ocean is also more strongly present at a depth of 300 m.

The concentrations of ^{137}Cs in the Southern waters of Java near the coast (stations 12–17) show a pattern of higher values to the east, with a range of 0.042–0.779 Bq m^{-3}. The results of previous studies in South Yogyakarta in the same season showed the concentration of Minimum Detection Activity (MDA) — 0.062 Bq m^{-3} (Suseno and Prihatiningsih, 2014). This near-shore water mass had a lower salinity, which shows that the water mass from the Pacific has been mixed with the waters of Indonesian waters (Fig. 4c). Indian Ocean water masses dominate further offshore (Fig. 4).

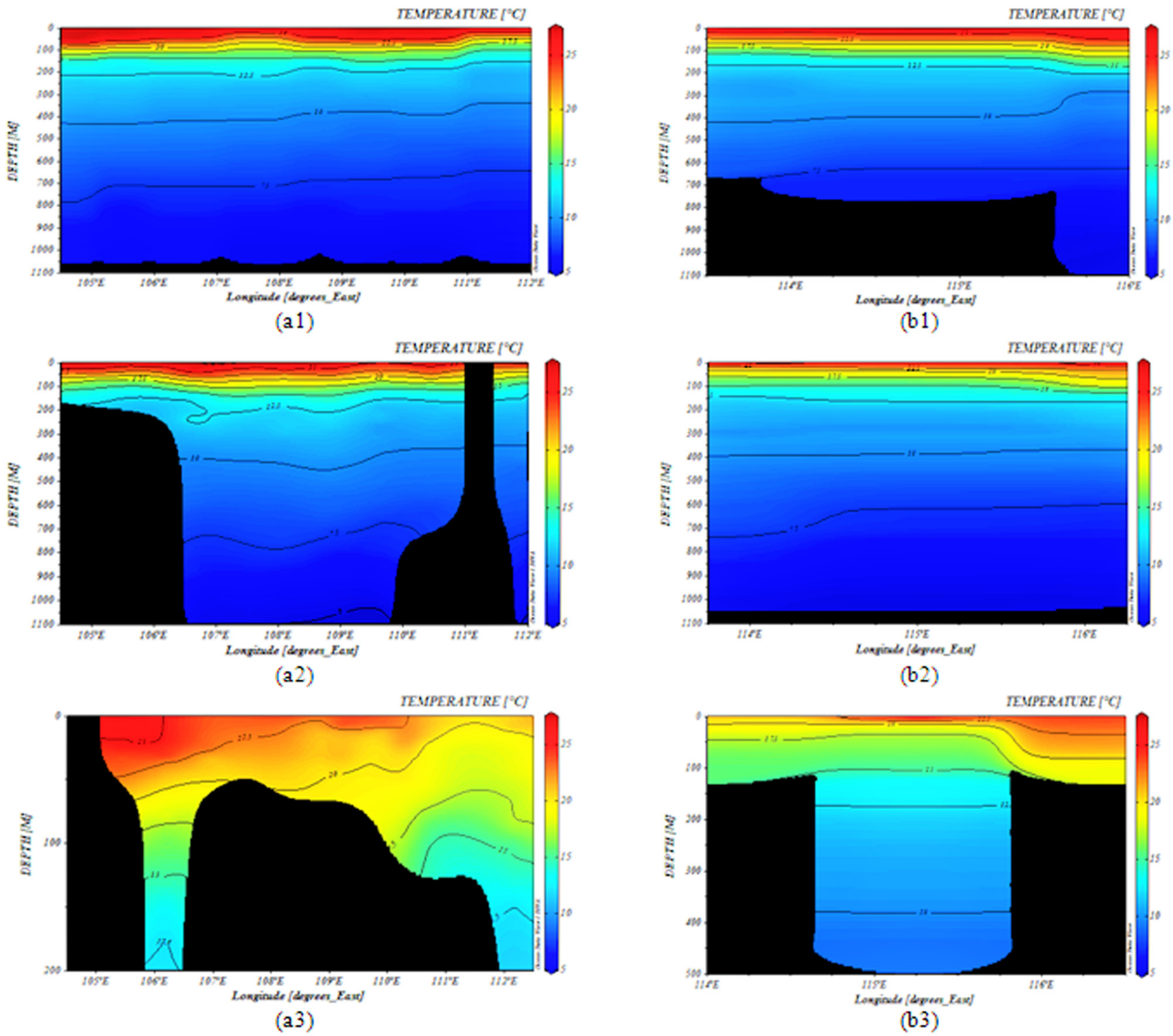

Fig. 3. Vertical distribution of temperature at Southern Java.

Table 3
Concentration of ^{137}Cs in seawater.

Station no.	Sampling date	Area	Depth (m)	Sampling depth (m)	Latitude	Longitude	Conc.^{137}Cs [Bq m^{-3}]
12	28/09/2015	SWJ	52	47	07°53.92′S	109°36.41′E	0.042
14	29/09/2015	SWJ	52	46	07°56.48′S	109°56.01′E	0.170
15	30/09/2015	SWJ	120	100	08°08.12′S	110°40.37′E	0.048
17	01/10/2015	SWJ	126	100	08°14.59′S	110°40.37′E	0.794
20	03/10/2015	SWL	150	100	08°42.24′S	114°03.47′E	0.074
21	04/10/2015	SWL	3885	1	09°25.37′S	114°59.03′E	0.136
				200			0.008
				1000			0.098
23	05/10/2015	SWL	3100	1	09°32.12 S	116°10.48 E	0.114
				200			0.795
				1000			0.680
24	05/09/2015	SWL	153	1	08°59.47′S	116°23.53′E	0.095
				100			0.784
25	05/09/2015	SWL	580	1	08°33.22′S	115°16.41′E	1.003
				100			0.058
				450			0,046

Note:
SJW = Southern Waters of Java.
SLW = Southern Waters of Lombok.

The water mass from Pacific is brought by the ITF and propagated westward by the Southeast Monsoon and the South Equatorial Current (SEC). This water mass is uplifted to the surface by strong upwelling between the longitudes of 107° E–114° E, and is increasingly strong at 112° E longitude. This phenomenon is

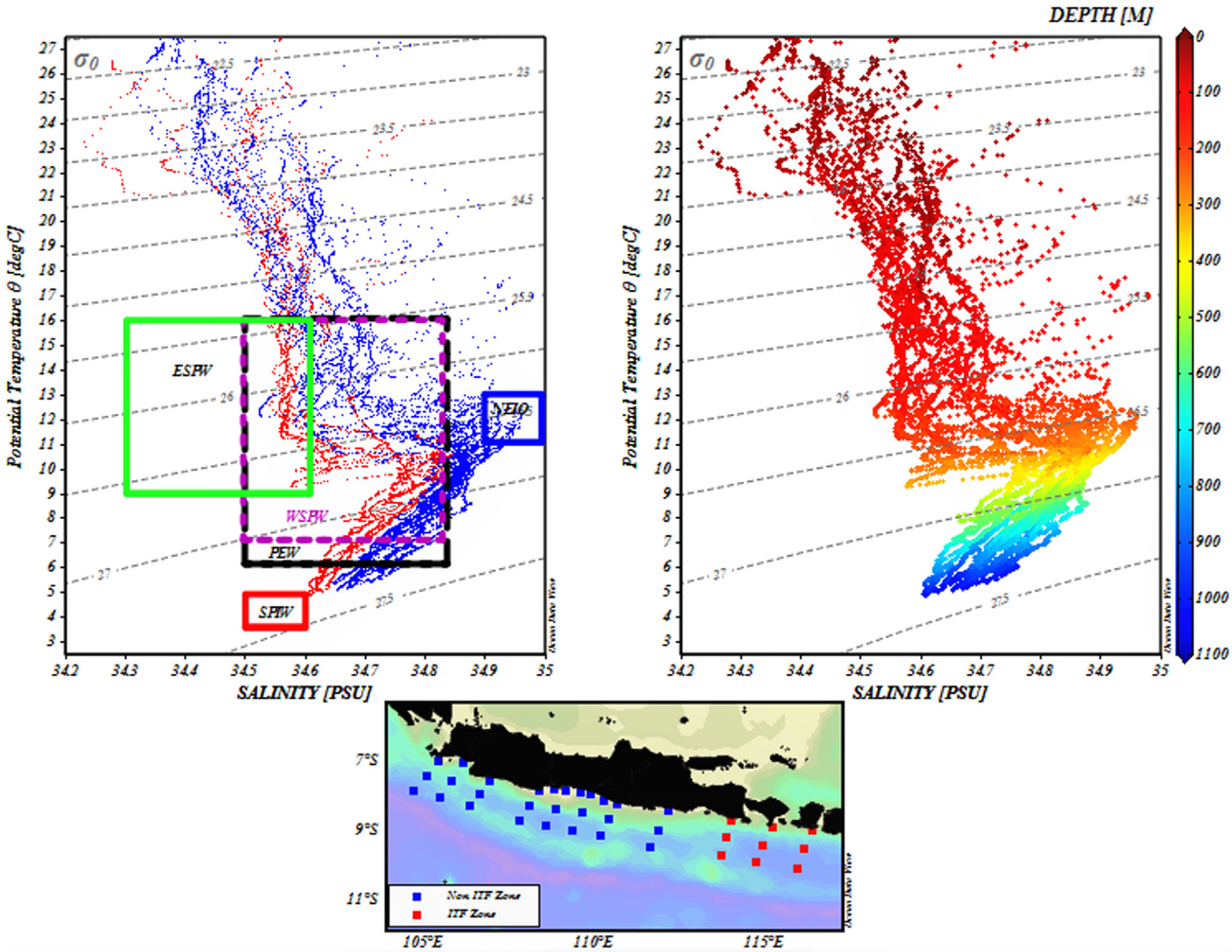

Fig. 4. T–S Diagram.

caused by the South Equatorial Current that moves towards the west and has a leftward direction due to the Coriolis force (Ilahude and Gordon, 1996). Therefore, the water mass of the surface layer moves following the SEC, especially near the coast, causing deeper water to be lifted. In addition, the second transition season of 2015 coincided with the strong IOD (Indian Ocean Dipole) (+) phenomenon in which Indonesian waters from the western coast of Sumatra to southern Java were under high pressure, causing air flow to the west and strengthening of the upwelling that occurred in southern Java.

The concentration of ^{137}Cs in seawater in the South Waters of Lombok (ITF Zone) shows a surface concentration value between 0.095–1.003 Bq m^{-3}, a thermocline layer concentration of 0.008–0.795 Bq m^{-3}, and a deep layer concentration of 0.046–0.680 Bq m^{-3}. Several previous studies (Suseno et al., 2015, 2017a,b; Suseno and Budi, 2018; Suseno and Prihatiningsih, 2014) have illustrated the general pattern the vertical distribution of ^{137}Cs in the ocean, but that do not show the regularity of the value from the surface to 1000 m. The vertical distribution of ^{137}Cs at the research location did not show the same pattern, which was probably caused by the influence of dynamic factors both local and remote. Fig. 5 shows the water mass of the Lombok Southern Waters consisting of several types, with the surface to 200 m influenced by low salinity water masses brought by nearby straits, and high salinity water masses present below 200 m water depth. Strong currents from the Alas strait and upwelling also contribute to the condition of these waters in the Southeast Season. (See Figs. 6 and 7.)

The concentration ratio of ^{134}Cs and ^{137}Cs is an indicator of the possible impact of the nuclear accident in Fukushima (Inoue et al., 2012b). When released into the waters, the ratio of the concentration of the two radionuclides is 1. The results of the radiocesium analysis showed that the concentration of ^{134}Cs in the Southern Waters of the Java and Lombok was lower than MDA, so the ratio of ^{137}Cs/^{134}Cs was below than 1. Based on this, the Southern Waters of Java and Lombok connected with one of the exit passages of the ITF have not been affected by the nuclear accident in Fukushima. It can then be safely concluded that the existence of ^{137}Cs in the ocean waters is derived from the atmospheric atomic bomb testing (global fallout).

4. Conclusion

Cesium ^{137}(137Cs) was detected at all the research stations with waters associated with the ITF exit passage, both in the Southern Waters of Lombok and in Java. The concentration of ^{137}Cs in the Southern Waters of Java near the coast (stations 12–17) showed a pattern of higher values to the east in the range 0.042–0.779 Bq m^{-3}. The concentration of ^{137}Cs in seawater in the Southern Waters of Lombok (ITF Zone) shows a surface concentration of 0.095–1.003 Bq m^{-3}, a thermocline layer concentration of 0.008–0.795 Bq m^{-3}, and a deep layer concentration of 0.046–0.680 Bq m^{-3}. In contrast, ^{134}Cs could not be detected in all the seawater samples taken. The presence of this radiocesium shows that the contaminated Pacific water mass reaches the Indian Ocean

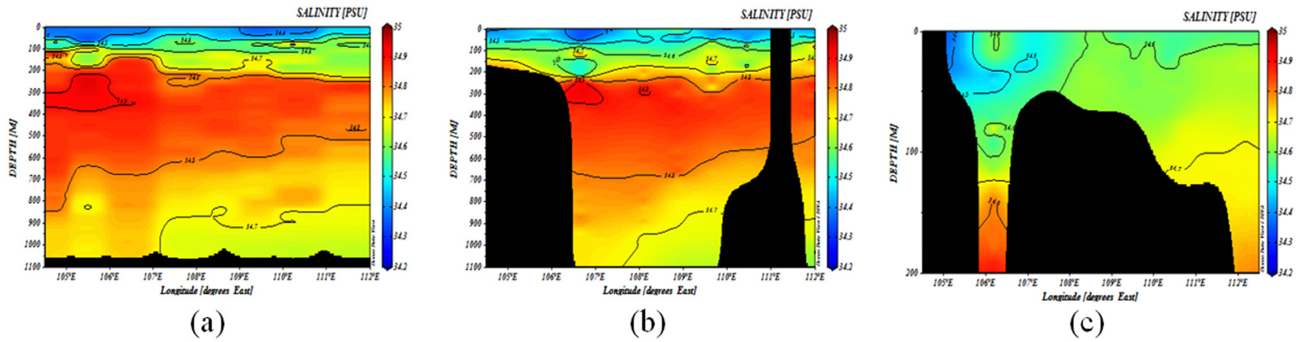

Fig. 5. Vertical Distribution of salinity on Southern Java.

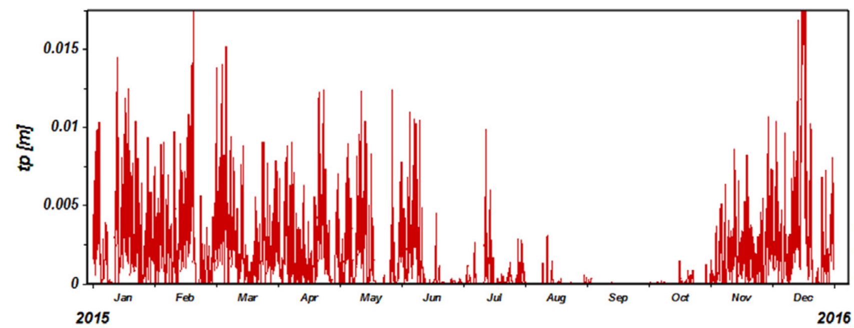

Fig. 6. Rain fall graph of Southern Java.

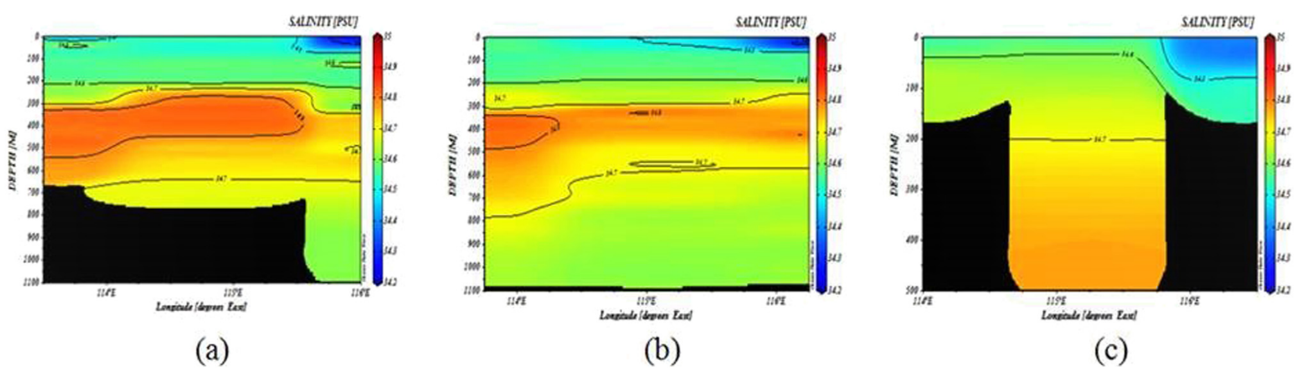

Fig. 7. Vertical distribution of salinity on Southern Java.

through the ITF exit passage, especially in the Southern Waters of Lombok and Java. The Pacific water mass entering the area of study is closely related to the ITF, the Southeast Monsoon winds, the South Equatorial Current, and upwelling phenomena and IOD (+). The existence of ^{137}Cs in the Southern Waters of Java and Lombok is derived from the atmospheric atomic bomb testing (global fallout).

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