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Baseline

Radiocesium monitoring in Indonesian waters of the Indian Ocean after the Fukushima nuclear accident

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ABSTRACT

As data on anthropogenic radionuclide concentrations (i.e., ^{134}Cs and ^{137}Cs) in Indonesian marine environments including the Indian Ocean are scarce, offshore monitoring has been performed in the West Sumatra and South Java Seas. The activity concentration of ^{137}Cs ranges from below minimum detectable activity (MDA) to 0.13 Bq m^{-3} in the surface seawater of the South Java Sea and from lower than MDA to 0.28 Bq m^{-3} in the surface seawater of the West Sumatra Sea. The concentrations of ^{137}Cs in the surface seawater of the West Sumatra and South Java Seas are lower than the estimation of ^{137}Cs concentration in the subsurface waters owing to the input of the North Pacific Ocean via the Indonesian Throughflow (ITF). The concentrations of ^{134}Cs in the sampling locations were lower than MDA. These results have indicated that these Indonesian marine waters have not yet been influenced by the Fukushima radioactive release.

Radiocesium (^{134}Cs and ^{137}Cs) is one of the radioactive materials present in the heavily contaminated coolant water that was discharged into marine water following the accident at the Tohoku Fukushima Dai-ichi nuclear power plant (FNPP) (Kaeriyama et al., 2013). The Kuroshio Current has subsequently transported isotopes of radiocesium and other radionuclides from Fukushima to the northwest (NW) Pacific Ocean (Nakano and Povinec, 2012). Due to their biogeochemical properties and oceanic processes, radionuclides from Fukushima can be transported from the NW Pacific Ocean to the Indian Ocean. The exchange of waters occurs in an inter-basin known as the Indonesian Throughflow/ITF (Sprintall et al., 2002, 2010).

Due to its possible impact on Indonesian marine waters and their biota, the accident at Fukushima has become a public concern in the country, as it relies heavily on the production of marine food products. Moreover, marine biota such as fish have the ability to accumulate ^{134}Cs and ^{137}Cs in their edible tissues from seawater, even when present in small concentrations. Java and Sumatra, two large Indonesian islands, lie adjacent to the eastern Indian Ocean, and they show considerable seasonal contrasting characteristics in their surface waters (Murgese et al., 2008). Some researchers have monitored the marine environment in Indonesia in relation to nuclear activities (research and application) and the potential threat posed by Fukushima releases. Radionuclide contaminants could already be influencing open ocean areas, thus calling for further development of a radionuclide-monitoring program in Indonesia. All environmental issues related to contaminants (including radionuclides) require a scientific foundation of understanding, monitoring, and modeling of the marine environment, which has not been established in Indonesian waters so far (Inagoos, 2005). The proposed monitoring program will be crucial to ensuring the safety of marine food products in Indonesia. At present, very limited data have been reported on the levels of anthropogenic radionuclides in the Indian Ocean (Povinec et al., 2011) as well as in the Indonesian marine waters, which are part of the Indian Ocean. The only comprehensive study was carried out in 1978 in the framework of the Geochemical Ocean Sections Study (GEOSECS) program, which included several vertical profiles of tritium in the water column (Povinec et al., 2011).

Analyzing the immediate and continuous records of these radionuclides in the marine environment following the FNPP accident is particularly important for obtaining the initial concentrations of ^{134}Cs and ^{137}Cs, because these are strongly affected by physical processes in seawater such as advection and mixing (Inoue et al., 2012). The ^{134}Cs and ^{137}Cs concentrations of highly contaminated surface seawater samples around the FNPP have been studied extensively (Tsumune et al., 2012; Honda et al., 2012), but such data on the waters surrounding the Indonesian archipelago are scarce. The possible impact of the Fukushima

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release on Indonesian coastal waters was recently studied in some coastal areas extending from the western to eastern regions of the archipelago (Suseno and Prihatiningsih, 2014). As data on offshore marine waters are unavailable, we monitored the ^{137}Cs and ^{134}Cs concentrations in the eastern Indian Ocean off the West Sumatran and South Java Seas. We participated in two scientific cruises of the research vessel *Baruna Jaya*, operated by the Technology Center for Marine Survey, Indonesian Agency for Assessment and Application of Technology. Samplings were carried out in the West Sumatra Sea between 20 and 28 November 2011 and in the South Java Sea between 16 and 20 September 2012. The results of the analysis highlight the possible impact of the accident at Fukushima on the Indonesian marine environment. On the other hand, the ^{137}Cs concentrations off the shore of Indonesia are very important because the elevated ^{137}Cs levels found in the South Indian Ocean subtropical gyre must therefore result from its transport from the North Pacific Ocean via the Indonesian seas.

The methods include surface water sampling and analysis of radiocesium concentration. Seawater sampling was carried out at five locations off West Sumatra and 10 locations off the South Java Sea (Fig. 1). Approximately 150 l of marine water samples were taken from each location. All samples from both regions were held in plastic containers and then transported to the marine radioecology laboratory at the Serpong Nuclear Area, Banten Province, Indonesia. The water samples for ^{137}Cs determination were prepared using methods similar to those of Yamada and Wang (2007) with some modifications. Briefly, the seawater samples were acidified to a pH of 1–2 with concentrated nitric acid. Radiocesium was separated from seawater by coprecipitation with the addition of 200 g of ammonium molybdophosphate (AMP) and an aliquot of CsCl solution containing 0.2–0.4 g of cesium as a carrier. After being left to stand for 24 h, the supernatant was separated out from the precipitate. Finally, the precipitates of AMP that contain ^{137}Cs were dried and placed in a plastic container before gamma counting. ^{137}Cs was determined using gamma rays at the photopeak of 661 keV. Each sample was measured for 259,200–345,600 s. We used three high-purity germanium (HPGe) detectors with counting efficiencies of 20–25% and a full width half maximum (FWHM) of 1.8 keV for a peak of 1332 keV of ^{60}Co. The gamma spectrometers used were Canberra GX2018, Canberra GC2020, and Ortec GMX 25P4-76. The method consisted of detector calibration, determination of detector counting efficiency, cumulative counts of both background and samples at regular intervals of time counted, photopeak smoothing, and linear regression.

Bailly du Bois et al. (2011) estimated the total activity of ^{137}Cs directly released from the Fukushima 1F NPP to be 27 ± 15 PBq. On the other hand, 160 and 15 PBq of ^{131}I and ^{137}Cs were estimated to be discharged into the atmosphere, respectively (Tsumune et al., 2012). More than 80% of the ^{137}Cs released into the atmosphere will also be deposited in the Pacific Ocean (Steinhauser et al., 2014). The FNPP is located within a transition area of the Kuroshio–Oyashio currents, an area between the extensions of the subarctic Oyashio and the subtropical Kuroshio. Therefore, dispersion of radiocesium eastward to the North Pacific is regulated by the Kuroshio Extension (KE) (Kaeriyama et al., 2013). Due to its chemical properties, radiocesium is soluble in seawater, which allows it to easily spread over long distances with marine currents as well as dissipate across oceanic water masses (Povinec et al., 2004). The Kuroshio Current is the dominant current in the NW Pacific Ocean that transports equatorial waters to the north. Furthermore, from the Pacific Ocean, masses of surface water stream down via the Indonesian seas to the Indian Ocean, subsequently penetrating the subtropical gyre (Povinec et al., 2011). The thermocline water from the North Pacific Ocean enters the Makassar Strait, whereas the lower thermocline water from the

Fig. 1. Sampling locations.

South Pacific Ocean is delivered to the Halmahera Sea (Gordon et al., 2010). The water surrounding Indonesia is exported to the Indian Ocean via three major passages: the Timor Passage, Ombai Strait, and Lombok Strait (Gordon et al., 2010). The South Java Current (SJC) flowing along the southern coast of the island of Java also affects the environmental condition of the Lombok Strait and its surrounding area on seasonal time scales (Inagoos, 2005). In the Indian Ocean (south of Java and West Sumatra), upwelling occurs between June and November in addition to the Ekman transport of surface water off the coast of Java and Sumatra resulting from the southeasterly winds (Baumgart et al., 2010; Gingele et al., 2002).

The ^{137}Cs and ^{134}Cs concentrations were monitored in the South Java and West Sumatra Seas in September 2011 and May 2012 onboard the research vessel of *Baruna Jaya*. These radionuclides in these locations following the FNPP accident need to be monitored to obtain the input of ^{134}Cs and ^{137}Cs. The results of the analysis of ^{137}Cs and ^{134}Cs concentrations in surface seawater are presented in Table 1. The activity concentration of ^{137}Cs in surface seawater at five locations of South Java Sea ranged from below minimum detectable activity (MDA) to 0.13 Bq m^{-3}. By contrast, the activity concentration of ^{137}Cs in surface seawater at 10 locations of the West Sumatra Sea ranged from lower than MDA to 0.28 Bq m^{-3}. In this study, The MDA for ^{137}Cs and ^{134}Cs were 0.01 and 0.02 Bq m^{-3}, respectively.

The conductivity, temperature, and depth (CTD) measurements of the South Java Sea (107°8′51″E; 07°44′23″S) were conducted. The results of these measurements are shown in Fig. 2. The sea surface temperature (SST) was 28.7 °C, and the temperature became 11.8 °C at a depth of 200 m. The salinity was 33.57 psu at the surface and 34.9 psu at a depth of 200 m. The neutral density was 21.9, which increased to 26.5 at a depth of 200 m. By contrast, the oceanography data on South Indian Ocean show that the SST varied between 22 and 28 °C, and the sea surface salinity (SSS) was within the interval 34.47–35.70 psu (Povinec et al., 2011). Our CTD data are comparable with the characteristics of the Indian Ocean.

Table 1
Concentration of radiocesium in surface water of the Indian Ocean (South Java and West Sumatra Seas).

Sampling site	Locations		Sampling time	Concentration (Bq m^{-3})	
	E	S		^{137}Cs	^{134}Cs
South Java					
	107°39.5′	07°38.9′	20 Sept 2012	0.14 ± 0.03	<MDA
	107°8.85′	07°44.37′	20 Sept 2012	0.30 ± 0.03	<MDA
	106°35.48′	07°49.93′	19 Sept 2012	0.26 ± 0.02	<MDA
	105°33.82′	08°00.20	19 Sept 2012	0.26 ± 0.02	<MDA
	105°31.52′	08°00′	18 Sept 2012	0.17 ± 0.02	<MDA
	105°24.41′	07°35.82′	18 Sept 2012	<MDA	<MDA
	105°22.08′	07°27.77′	17 Sept 2012	0.14 ± 0.01	<MDA
	105°17.47′	07°11.24′	17 Sept 2012	<MDA	<MDA
	105°12.52′	06°54.44′	16 Sept 2012	0.21 ± 0.02	<MDA
	105° 23.1′	06°32.58′	16 Sept 2012	0.28 ± 0.03	<MDA
West Sumatra					
	101°31.667′	05°01.667′	20 Nov 2011	<MDA	<MDA
	103°20.000′	05°36.667′	21 Nov 2011	<MDA	<MDA
	095°30.300′	06°59.800′	23 Nov 2011	0.11 ± 0.02	<MDA
	097°30.830′	06°47.330′	23 Nov 2011	0.10 ± 0.03	<MDA
	099°30.467′	06°31.500′	24 Nov 2011	0.13 ± 0.03	<MDA

MDA ^{137}Cs = 0.01 Bq m^{-3}, MDA ^{134}Cs = 0.02 Bq m^{-3}

Suseno and Prihatiningsih (2014) compared the ^{137}Cs data at some Indonesian coastal sites obtained between the years 2011 and 2013, reporting activity levels of ^{137}Cs in surface waters between 0.12 and 0.32 Bq m^{-3}. This comparison indicates that the ^{137}Cs concentrations were similar to those determined in the South Java and West Sumatra Seas in the present study. Kameník et al. (2013) reported that the average ^{137}Cs concentration in Hawaii after the Fukushima accident was 1.46 ± 0.06 Bq m^{-3}. Povinec et al. (2011) explained that the concentration of ^{137}Cs in surface water around 60 and 110°E can be correlated with the transport of mass water via the ITF to the South Indian Ocean. Furthermore, Povinec et al. (2011) used the activity ratio of ^{137}Cs/^{3}H generated during the GEOSECS and World Ocean Circulation Experiment (WOCE) programs to predict the concentration level of ^{137}Cs at some locations in the Indian Ocean. Based on these predictions, the ^{137}Cs concentrations in subsurface seawater at 100°E were 2.1 Bq m^{-3} (decay correction at 1 January 2004). Furthermore, the subsurface water mass enters the North Pacific Ocean via the ITF. Our monitoring at 99–103°E has shown that the concentration in the surface water ranged from below MDA to 0.13 Bq m^{-3}. The decay correction (at November 2011) indicated that the ^{137}Cs concentration in the surface water at these locations were lower than that in the subsurface water. Furthermore, Jha et al. (2012) reported that the concentration of ^{137}Cs in the Indian coastal area ranged between 0.3 and 1.25 Bq m^{-3}. Inoue et al. (2012) reported that the peak concentration of ^{137}Cs in the Tsugaru Strait and off western Hokkaido was 2.5 Bq m^{-3} in June 2011.

We assumed the radiocesium at the Tsugaru Strait and off western Hokkaido to be one of the sources of ^{137}Cs released from the Fukushima site, which then entered into the Pacific Ocean (Hawaii) via the Kuroshio Current and subsequently reached the Indonesian seas (South Java and West Sumatra). Based on these assumptions and data, the ^{137}Cs concentration will have decreased in the Pacific Ocean and become lower in the Indonesian seas. The ^{137}Cs discharged from Fukushima will be diluted in both the Pacific Ocean and Indonesia's seawater. The concentration of ^{137}Cs is lower in the South Java and West Sumatra Seas than in the Pacific Ocean. Over 30 cm/month of monthly rainfall on the shore of the Indian Ocean and Sumatra is observed, with the river water being discharged into the ocean (Murgese et al., 2008). The comparison between ^{137}Cs and ^{134}Cs concentration in the Asia Pacific regional seawater is shown in Table 2.

The concentration of ^{137}Cs in the surface water of the Pacific Ocean before the FNPP accident was 1–2 Bq m^{-3}, which was derived from the nuclear weapon tests mostly undertaken in the 1950s and 1960s (Livingston and Povinec, 2000), therefore being overtaken by Fukushima-derived ^{137}Cs (Kumamoto et al., 2013). The ratio of ^{137}Cs to ^{134}Cs evidenced the discharge of ^{137}Cs from Fukushima, and the value was 1 at 2011(Maderich et al., 2013; Kumamoto et al., 2013). The results of our analysis showed that the concentration of ^{134}Cs in the South Java Sea and West Padang was lower than MDA. Using a model of the Fukushima accident, Nakano and Povinec (2012) estimated that the maximum ^{137}Cs concentration in the NW Pacific Ocean will have reached 21 Bq m^{-3} in 2012, which is comparable with the estimated levels from global fallout in the early 1960s. Nakano and Povinec (2012)

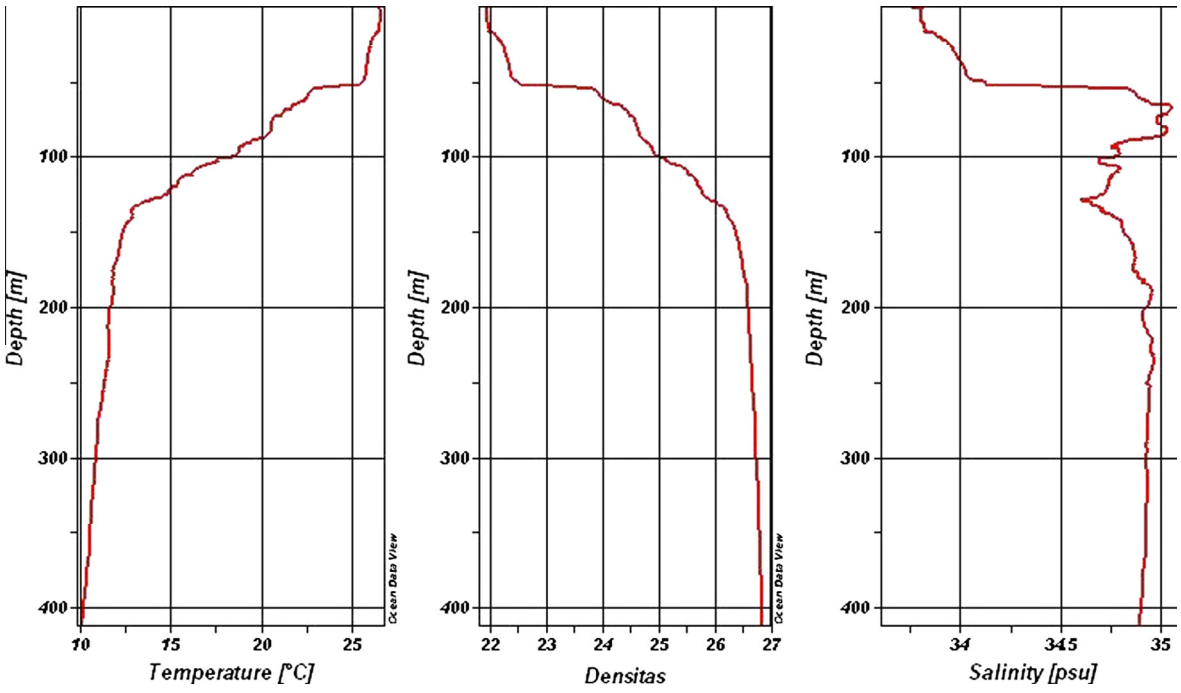

Fig. 2. CTD data.

Table 2
Comparison of ^{137}Cs concentration in Asia Pacific regional seawaters.

Region	Concentration of ^{137}Cs (Bq m^{-3})	Reference
North Indian Ocean	1.6	Povinec et al. (2004)
Coastal area of Arabian Sea, India	0.71–0.19	Jha et al. (2012)
Japan	0.93–2.86	Inoue et al. (2012)
Hawaii	1.46 ± 0.06	Kameník et al. (2013)
Indonesian coasts	0.13–0.32	Suseno and Prihatiningsih (2014)
Indian Ocean (estimated at 60 and 110°E at 1 January 2004)	2.1 Bq m^{-3}	Povinec et al. (2011)
South Java Sea (Indian Ocean)	<MDA–0.13	Present study
West Sumatra Sea (Indian Ocean)	<MDA–0.28	Present study

also estimated that the concentration will rapidly decrease with time, reaching <1 Bq m^{-3} in 2021.

In conclusion, the activity concentration of ^{137}Cs in the surface seawater of the South Java Sea ranged from below MDA to 0.13 Bq m^{-3}. On the other hand, the activity concentration of ^{137}Cs in the surface seawater of the West Sumatra Sea ranged from below MDA to 0.28 Bq m^{-3}. The concentration was comparable with the concentration data in the Asia Pacific Regions. The concentration of ^{137}Cs in the surface seawater of the West Sumatra and South Java Seas is lower than the estimation of ^{137}Cs concentration in the subsurface seawater due to input of the North Pacific Ocean via the ITF. The results of the analysis showed that the concentration of ^{134}Cs in the South Java Sea and West Padang was lower than MDA, so the ratio of ^{137}Cs/^{134}Cs was not unity. These results indicated that Indonesian marine water has not been influenced by the Fukushima radioactive release.

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