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Role of mesoscale eddies in transport of Fukushima-derived cesium isotopes in the ocean

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ABSTRACT

We present the results of *in situ* measurements of ^{134}Cs and ^{137}Cs released from the Fukushima Nuclear Power Plant (FNPP) collected at surface and different depths in the western North Pacific in June and July 2012. It was found that 15 month after the incident concentrations of radiocesium in the Japan and Okhotsk seas were at background or slightly increased level, while they had increased values in the subarctic front area east of Japan. The highest concentrations of ^{134}Cs and ^{137}Cs up to 13.5 ± 0.9 and 22.7 ± 1.5 Bq m^{-3} have been found to exceed ten times the background levels before the accident. Maximal content of radiocesium was observed within subsurface and intermediate water layers inside the cores of anticyclonic eddies (100–500 m). Even slightly increased content of radiocesium was found at some eddies at depth of 1000 m. It is expected that convergence and subduction of surface water inside eddies are main mechanisms of downward transport of radionuclides. *In situ* observations are compared with the results of simulated advection of these radioisotopes by the AVISO altimetric velocity field. Different Lagrangian diagnostics are used to reconstruct the history and origin of synthetic tracers imitating measured seawater samples collected in each of those eddies. The results of observations are consistent with the simulated results. It is shown that the tracers, simulating water samples with increased radioactivity to be measured in the cruise, really visited the areas with presumably high level of contamination. Fast water advection between anticyclonic eddies and convergence of surface water inside eddies makes them responsible for spreading, accumulation and downward transport of cesium rich water to the intermediate depth in the frontal zone.

1. Introduction

The great Tohoku earthquake of magnitude 9.0 on 11 March 2011 followed by the tsunami inflicted heavy damage on the Fukushima Nuclear Power Plant (FNPP) due to overheating the reactors and hydrogen explosions. Large amount of radioactive water leaked directly into the ocean (Tsumune et al., 2012; Kanda, 2013). Moreover, the radioactive pollution of the sea was also caused by atmospheric deposition on the ocean surface (Takemura et al., 2011; Miyazawa et al., 2013). Radioactive cesium with 30.17 yr half-life for ^{137}Cs and 2.06 yr half-life for ^{134}Cs has been detected over a broad area in the North Pacific in 2011 and 2012 (Honda et al., 2012; Buesseler et al., 2012; Inoue et al., 2012a, 2012b; Kaeriyama et al., 2013, 2014; Oikawa et al., 2013; Aoyama et al., 2013; Kameník et al., 2013**?**). ^{137}Cs is a passive tracer in seawater which can be used to study long-term circulation and ventilation of water masses in the global ocean. In particular, distribution of Fukushima-derived ^{137}Cs in the ocean would help to validate numerical circulation models and their parameters.

The area east of Japan is known as Kuroshio–Oyashio confluence zone (Kawai, 1972) or subarctic front area. Existence of a large number of mesoscale eddies in this area should influence the transport of water contaminated with Fukushima-derived radionuclides. Among these eddies, the Kuroshio warm core rings are most energetic and long-lived ones (see, e.g., Kitano, 1974; Itoh and Yasuda, 2010a). Strong and persistent anticyclonic eddies are also observed along the Kuril Islands (Bulatov and Lobanov, 1992; Yasuda et al., 2000).

Both cyclonic and anticyclonic eddies would provide fast transport of surface water by streamers. However, because of a divergence in the cyclonic eddies one may expect upwelling of deep water and thus lower concentration of radionuclides in the surface layer. In opposite, we may expect accumulation of contaminated water in anticyclonic eddies because of convergence in their surface layer and following subduction to the deeper ocean. In addition, winter

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convection should increase penetration of contaminated water to deeper layers inside anticyclonic eddies in comparison with surrounding waters.

It is known that Kuroshio warm-core rings may move northeastward toward the Kuril Islands (Lobanov et al., 1991; Bulatov and Lobanov, 1992; Yasuda et al., 1992; Itoh and Yasuda, 2010a) and thus transport trapped water with a higher cesium content to the north of the subarctic front. To prove this hypothesis we have performed a numerical modelling of tracer transport in the area east of Japan and implemented a cruise to cross major streams and eddies in the area using R/V "Professor Gagarinskiy" of the Far Eastern Branch of Russian Academy of Sciences. The cruise has been conducted from 12 June to 10 July 2012, 15 months after the accident.

We focus here on comparing the experimental results, obtained with water samples at stations in the centers of some selected anticyclonic eddies in the region, with the results of numerical simulation of spatial distribution of Fukushima-derived radionuclides. The simulation helps to explain why we have detected comparatively high cesium concentrations in the cores of some eddies and lower ones in the other eddies.

The paper is organized as follows. In Section 2 we briefly present for comparison the results of previous direct observations of ^{134}Cs and ^{137}Cs in the area of the western North Pacific (Honda et al., 2012; Buesseler et al., 2012; Kaeriyama et al., 2013) where some of our sampling stations were located. Section 3 describes the cruise track, sample collection, the methods of radioactive analysis and computation. The numerical Lagrangian methods we used are based on solving advection equations for synthetic particles in an altimetric velocity field provided by AVISO. Section 4 contains the main results and a discussion. We present a table summarizing the results of our measurements of the concentration of ^{134}Cs and ^{137}Cs in seawater samples collected at different depth horizons in the broad area in the Sea of Japan, the Okhotsk Sea and the western North Pacific. Simulation results are plotted as tracking maps revealing origin and history of water masses collected at representative sampling stations where different values of concentration of ^{134}Cs and ^{137}Cs have been observed. They are compared with the corresponding measurements. In this section we analyze as well vertical cross-section of potential density anomaly, potential vorticity, distribution of cesium isotopes in surface water along the cruise track and vertical distribution of ^{134}Cs and ^{137}Cs at some selected stations. It is also discussed why measured activities of cesium differs strongly at different stations. Results are summarized in Section 5.

2. Previous observations of Fukushima-derived cesium

Before March 2011, ^{137}Cs concentration levels off Japan were 1–2 Bq m^{-3} $\simeq$ 0.001–0.002 Bq kg^{-1}, while ^{134}Cs was not detectable. Because of a comparatively short half-life time, any measured concentrations of ^{134}Cs could only be Fukushima derived. Concentrations at the FNPP discharge channels in early April 2011 were more than 50 million times greater than the preexisting ocean level of ^{137}Cs (Buesseler et al., 2012).

One month after the accident, sea-water, suspended solids and zooplankton samples were collected from the surface mixed layer and subsurface layers at a number of stations, 200–2000 km offshore from the FNPP (Honda et al., 2012). In surface water, ^{137}Cs concentrations were ranged from several times to two orders of magnitude higher than before the accident. ^{134}Cs isotope was also detected with the ratio ^{134}Cs/^{137}Cs to be about 1. The highest concentrations, from $\approx$150 Bq m^{-3} to $\approx$350 Bq m^{-3}, have been found off the FNPP ($\approx$200 km from the nuclear power plant) and Miyagi (the earthquake source). ^{137}Cs concentrations to the east of this region in the area (146–147°E; 37–38°N) were also high ($\approx$50–60 Bq m^{-3}). The ^{137}Cs concentrations in the Kuroshio Extension, $<$10 Bq m^{-3}, were low, because it was considered to be the main potential pathway for contaminated water to the open ocean.

The expedition of the Russian Hydrometeorological Service on R/V "Pavel Gordienko" in 24 April–6 May 2011 (Karasev, 2012) proved increased concentration of both ^{137}Cs and ^{134}Cs in surface water along the whole Kuril Island chain (2.2–3.6 Bq m^{-3} and 1.2–2.9 Bq m^{-3}, correspondingly) but not at the southern part of the Kamchatka Peninsula, where those concentrations were 1.4 and 0.4 Bq m^{-3}, correspondingly. Such distribution of radionuclides could be explained by atmospheric transport. They also found high concentration of radionuclides in the area about 350 km east of Tohoku, where ^{137}Cs and ^{134}Cs contents were found to be up to 24 and 21 Bq m^{-3}, correspondingly.

The R/V "Ka'imikai-o-Kanaloa" cruise has been conducted in 4–18 June 2011 by Buesseler et al. (2012) to investigate the distribution of Fukushima-derived radionuclides in seawater, zooplankton and micronectonic fishes 30–600 km offshore from the FNPP. Activities up to 325 Bq m^{-3} were found more than 600 km offshore. As to ^{137}Cs, the highest level (except for the discharge channels), 600–800 Bq m^{-3}, has been detected 30 km offshore. In June, Fukushima-derived Cs did not generally penetrate below 100–200 m. Over time, it is expected to find deeper penetration proving a means to study the rates of vertical mixing processes in the Pacific. Fukushima-derived isotopes have been also detected in zooplankton (with the maximal level about 5×10^4 Bq m^{-3} dry weight comparable with the recommended value of 4×10^4 Bq m^{-3}) and jellyfish but not in micronectonic fishes. In June 2011, the highest surface-water concentrations for both the isotopes, 3.9×10^3 Bq m^{-3}, have been detected in a semipermanent mesoscale eddy centered at (142.5°E; 37°N), not the nearest location to the nuclear power plant.

Results of direct observation of ^{134}Cs and ^{137}Cs in surface seawater collected from R/V "Kaiun maru" in a broad area in the western and central North Pacific in July, October 2011 and July 2012 have been reported by Kaeriyama et al. (2013). In particular, seawater samples were collected at their stations C43–C55 (26–29 July 2011) located from 35°N to 41°N along the 144°E transect with its southern edge crossing a crest of the Kuroshio Extension meander and the northern edge crossing partly the Tohoku mesoscale eddy centered at that time at ($\approx$144°E; 38°N). The eddy is a warm-core Kuroshio ring permanently present in the region till the end of our cruise and later. It is clearly seen in an earlier simulation of Fukushima-derived radionuclides propagation (see Prants et al., 2011b, Fig. 3b) and in the present one marked by letter 'T' on the Lagrangian maps in Fig. 3. During 15 months after the accident, that eddy has interacted with a number of adjacent eddies and streamers promoting transport of contaminant water to the north, south and east. The measured ^{137}Cs concentrations at stations C43–C55 have been varied from the background level of 1.9 $\pm$ 0.4 Bq m^{-3} (station C52) to 153 $\pm$ 6.8 Bq m^{-3} (station C47). The ratio ^{134}Cs/^{137}Cs was close to 1.

3. Materials and methods

The cruise on the board of R/V "Professor Gagarinskiy" was conducted with the aim to collect data on the distribution of artificial radionuclides after the accident at the FNPP in the area of the Japan Sea, Sea of Okhotsk and the adjacent area of the Northwest Pacific (Fig. 1). We used standard methods to collect water and biota followed by laboratory processing and detection of ^{134}Cs and ^{137}Cs with a high-purity germanium spectrometer.

3.1. Sample collection

During the cruise, conducted from 12 June to 10 July 2012, surface water samples were collected along the cruise track by a