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Evaluation of radioactive cesium impact from atmospheric deposition and direct release fluxes into the North Pacific from the Fukushima Daiichi nuclear power plant

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ABSTRACT

The North Pacific distribution of ^{134}Cs released from the Fukushima Daiichi nuclear power plant (F1NPP) has been investigated using an eddy-resolving model. We conducted simulations based on two scenarios: (1) an input flux that was a combination of atmospheric deposition and direct release from the F1NPP (combination-flux scenario) and (2) an input flux that took account only of the direct release of ^{134}Cs (single-flux scenario). The combination-flux scenario simulation successfully reproduced the distribution of ^{134}Cs activity observed in the surface layer from April 2011 to January 2014. The results indicate that ^{134}Cs deposited via atmospheric deposition into the Kuroshio-Oyashio Interfrontal Zone and ^{134}Cs directly released from F1NPP were both transported to south of the Subarctic Front around 42°N in June of 2012. The combination-flux scenario suggests that the ^{134}Cs activities observed in the area north of 42°N in 2012 originated from atmospheric deposition and that the ^{134}Cs activity was subducted in Central Mode Water during the winters of 2011 and 2012. We directly compared simulated and observed ^{134}Cs activities in the surface layer at 179 points across a wide area to the east of 155°E from 2011 to 2013 to evaluate the accuracy of the two scenarios. The root-mean-square error and correlation coefficient, R, were 7.3 Bq m^{-3} and 0.86, respectively, for the combination-flux scenario and 13.8 Bq m^{-3} and 0.46, respectively, for the single-flux scenario, confirming that reproduction of the ^{134}Cs activity in the North Pacific after the F1NPP accident requires taking both fluxes into consideration. Based on a linear least-squares regression between simulated and observed ^{134}Cs activity, the total ^{134}Cs flux into the North Pacific was estimated at 16.1 ± 1.4 PBq.

1. Introduction

On 11 March 2011, the cooling facilities of the Fukushima Daiichi nuclear power plant (F1NPP), operated by the Tokyo Electric Power Company (TEPCO), were damaged by the tsunami that followed the Tohoku earthquake, resulting in a nuclear accident. As a result, ^{134}Cs and ^{137}Cs (hereafter radioactive cesium) were released to the environment from the F1NPP.

Radioactive contamination of the North Pacific Ocean occurred through two major pathways: atmospheric release, transport and deposition caused by the hydrogen explosion and ventilations at the F1NPP, and leakage of heavily contaminated coolant water from the F1NPP directly into the ocean (Tsumune et al., 2013). Contamination from both the main sources persisted for approximately two months after the F1NPP accident. Initial estimates indicated that the atmospheric deposition of radioactive cesium into the North Pacific accounted for 6 PBq of the estimated total of 9 PBq of each radioactive cesium isotope that was released to the atmosphere from the F1NPP (Terada et al., 2012). More recent estimates indicate that the atmospheric deposition of each isotope into the North Pacific was about 12 PBq of the total of 14.5 PBq released to the atmosphere from the F1NPP (Katata et al., 2015), and airborne monitoring has indicated that the total deposition of ^{137}Cs on the land surface of Japan was about 2.4 PBq (Morino et al., 2013). Estimates of the total amount of radioactive cesium discharged directly to the ocean have ranged from 3.6 to 5.9 PBq (TEPCO, 2012; Kawamura et al., 2011; Tsumune et al., 2012, 2013; Miyazawa et al., 2013). The net input of 10–18 PBq of ^{137}Cs

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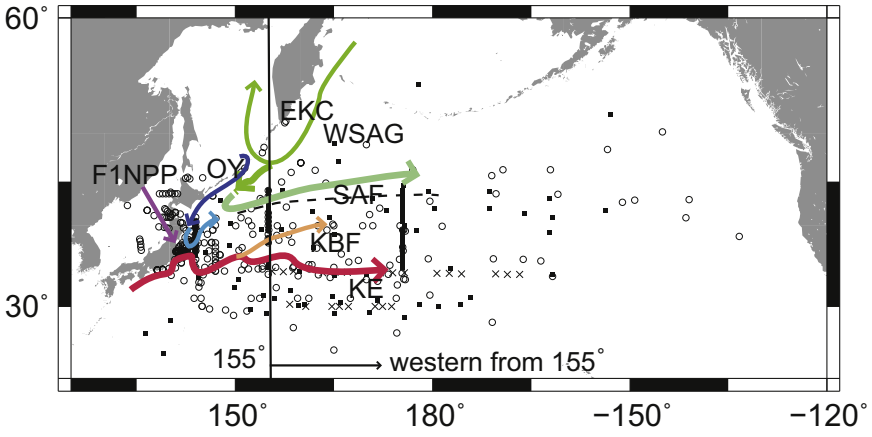

Fig. 1. Schematic illustration of the near-surface currents in the study region, the Subarctic and Kuroshio bifurcation fronts (Yasuda, 2003), the observation sites from 2011 to 2013, and the location of the F1NPP. EKC: East Kamchatka Current (green arrow), WSAG: Western Subarctic Gyre (light green arrow), OY: Oyashio Current (blue and light blue arrow), KE: Kuroshio Extension (red arrow), KBF: Kuroshio Bifurcation Front (orange arrow), SAF: Subarctic Front (dotted line). The open circles, black squares, and crosses indicate observation sites in 2011, 2012, and 2013, respectively. The black vertical line indicates meridional line at 155°E. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

corresponds to 15–20% of the total amount (69 PBq) of ^{137}Cs that was present in the North Pacific before the F1NPP accident (Aoyama et al., 2012a).

The North Pacific spatial and temporal distributions of the radioactive cesium activities in seawater derived from atmospheric deposition were distinct from those directly released into the ocean during the period immediately following the F1NPP accident. The radioactive cesium from atmospheric deposition was distributed widely over the surface of the North Pacific during a relatively short period (about 50days) following the accident, whereas that directly released from the F1NPP was transported to the central North Pacific by the surface current system as a radioactive Cs plume after dilution and mixing in coastal waters. The former might be regarded as a plane source distributed widely, whereas the latter one can be regarded as a point source.

The area offshore of the F1NPP lies adjacent to the region where the Kuroshio (or Kuroshio Extention: KE) and the Oyashio currents approach each other and then separate from the coast (Fig. 1). Simulation of the radioactive cesium activities from both sources requires a model that resolves mesoscale eddies in order to accurately reproduce the Kuroshio separation, KE and Oyashio currents (e.g., Hasumi et al. (2010)). Rossi et al. (2013, 2014) and Kawamura et al. (2014) investigated the radioactive cesium activity in the North Pacific using Lagrangian particle models with currents derived from eddy-resolving models. Behrens et al. (2012) simulated the cesium activity in the North Pacific using an Eulerian model with eddying resolution. Rossi et al. (2013) and Behrens et al. (2012) studied the basin-scale dispersion or plume pathway of the cesium activity by inputting within the 30 km to 150 km area around the F1NPP, that is, from the point source. Kawamura et al. (2014) simulated the cesium activity from the atmospheric deposition and direct release and showed that the simulation results agreed with the observations in March to May 2011. Kawamura et al. (2014) also conducted a simulation of the cesium activity from a direct release alone. They show that atmospheric deposition was responsible for the widely distributed relatively high concentrations in the western North Pacific in early period (April to May in 2011) after the accident. They also show that differences in the early distribution of the cesium activities between the two input sources led to differences in their respective arrival period to the central of the North Pacific. These early results suggest that comparison of simulation output with intense observations (Fig. 1) over an extended period (Aoyama et al., 2012a, 2012b, 2012c, 2013; Buesseler et al., 2011, 2012; Honda et al., 2012; Kaeriyama et al., 2013) will enable us to investigate the derivation of observed radioactive cesium, the arrival period in different regions of the North Pacific, as well to evaluate the total amount of radioactive cesium input to the North Pacific from both sources..

In addition to differences in the surface concentrations resulting from the two input sources, we expect differences in the contributions to temporal evolution of subsurface concentrations as well. Late winter surface radioactive cesium between the KE and Sabarctic Front (SAF) was subducted in association with the formation of the Central Mode Water (CMW; Nakamura (1996), Suga et al. (1997) and Oka and Qiu (2012)). Kumamoto et al. (2014, 2015) found the relatively high ^{134}Cs activities around 200–400 m from 24°N to 34°N, corresponding to subtropical mode water (STMW: Masuzawa (1969)) along 149°E from December 2011 to February in 2012. Aoyama et al. (2015a) detected ^{134}Cs activities down to a depth of 600 m from 29°N to 39°N along 165°E in July 2012. The particles released within 30 km around F1NPP in the simulation of Rossi et al. (2013) penetrated down to 500 m around 40°N, corresponding to CMW, and concentrated around 200 m south of 30°N, along 165°E corresponding to STMW in about one year. This result suggests that the F1NPP-derived ^{137}Cs will be available as a potential tracer of several mode waters in the North Pacific in the future because of its long radioactive half-life. Aoyama et al. (2008) detected the maxima of ^{137}Cs activity from the fallout of atmospheric nuclear weapons tests at depths of 200 and 400 m, corresponding to the depths of STMW and CMW around 20°N along a 165°E section in 2002. In order to best use radioactive cesium as a tracer of mode waters, it is important to determine the time when the radioactive cesium was deposited in the formation region.

In this study, we first focus on the difference in the spatial distributions of the radioactive cesium activities from the plane and point sources for the two month period following the accident. We then examine the discrepancy between simulated and observed distributions for a period of a few years in each experiment. The discrepancy enables us to elucidate from which sources the observed radioactive cesium activities in the North Pacific originated and when the radioactive cesium activity was transported into the subsurface in association with the subduction of CMW. We next assess the total amount of the radioactive cesium activity from the F1NPP that was released into the Pacific Ocean from both sources based on a combination of the simulated results and observations.