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Interactive comment on "Ocean dynamic processes causing spatially heterogeneous distribution of sedimentary caesium-137 massively released from the Fukushima Dai-ichi Nuclear Power Plant" *by* H. Higashi et al.

H. Higashi et al.

higashi@nies.go.jp

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We are grateful to the referee for her/his comments that help us to improve our manuscript. Our responses are described below.

Referee #2 comment:

(P.12729, L.25 – P.12730, L.6) You cannot really say that your results are "largely consistent with the earlier simulations". The simulation result from the end of March to

the beginning of April of Fig. 4(a) seems 0.1 times of the observation. This tendency of underestimation is stronger than 0.5 times of Fig. 10(a) of Miyazawa et al. (2013). Quite large amount of Cs-137 measured around 1FNPP during the period from March 26 to April 9. The initial bottom sediment contamination was strongly affected by the surface Cs-137 concentration of this period. Examining the results from March 26 to April 9 of Fig. 4(a), in spite of using direct discharge from 1FNPP like Miyazawa et al. (2013) and extremely huge amount of atmospheric deposition, I believe this outcome is not supported clearly enough.

Response:

One of the reasons of the discrepancy between surface-seawater ^{137}Cs simulated by our model and that by Miyazawa et al. (2013) is ^{137}Cs behaviours of adsorption to suspended particulate matter and subsequent downward sinking that are considered in our model, but not in the Miyazawa's model. These processes including resuspension and horizontal transport play important roles for ^{137}Cs migration from seawater to seabed and redistribution of sedimentary ^{137}Cs (Otosaka and Kobayashi, 2013). They were usually considered in previous models for simulating ^{137}Cs sedimentation (e.g., Kobayashi et al., 2007; Periáñez et al., 2012; Choi et al., 2012) as with our study. As a result of the ^{137}Cs sinking, seawater-surface ^{137}Cs simulated by our model would be smaller than that by the Miyazawa's model, if identical ^{137}Cs inflow condition were given. By contrast, our simulation needs larger atmospheric ^{137}Cs deposition than Miyazawa's simulation to produce same surface-seawater ^{137}Cs activity. This also indicates that ^{137}Cs inflow of direct discharge and atmospheric deposition estimated by Miyazawa et al. (2013) would be underestimated if the ^{137}Cs sinking were not negligible.

Another reason of the discrepancy between surface-seawater ^{137}Cs simulated by our model and that by Miyazawa et al. (2013) is that our spatiotemporal variation in atmospheric ^{137}Cs deposition is probably different from that used in Miyazawa et al. (2013), as a matter of course. Hence, our atmospheric ^{137}Cs deposition at anywhere or anytime do not necessarily exceed that used by Miyazawa et al. (2013), even though the

total amount of atmospheric ^{137}Cs deposition over the ocean in the former simulation are larger than that in the latter.

For the above reasons of the differences in the numerical procedures and/or the simulation conditions, there was no earlier simulation that quite quantitatively agreed with our spatiotemporal distribution of the seawater ^{137}Cs. Hence, the referee comment of "You cannot really say that your results are largely consistent with the earlier simulations" is absolutely right. Meanwhile, we confirmed that our seawater ^{137}Cs dispersion (Figs. 4 and S2) was qualitatively consistent with the earlier simulations. For instance, the discrepancy between our simulation and the observation had similar characteristics in the earlier studies as follows: our simulation tended to underestimate sea-surface ^{137}Cs southeast of 1FNPP such as at stations W-8–10 (Fig. 4g–i) per the earlier simulations (Kawamura et al., 2011; Tsumune et al., 2012; Miyazawa et al., 2013). We will revise Sect. 3.1 (P. 12729, L1 – P. 12730 L6) as a below section Revise #2-1 to show the above description briefly.

In addition, we consider that quantitative uncertainty of our results should be also described briefly and more clearly. The atmospheric ^{137}Cs deposition is one of the factors of the uncertainty. The spatiotemporal variation of atmospheric ^{137}Cs deposition over the ocean, which has been estimated using numerical simulations by several previous studies besides Miyazawa et al. (2013) and Morino et al. (2011), included relatively large uncertainty and its total amount ranged very widely (e.g., 5 PBq within 30.5–48.0N, 127.0–154.5E through the end of April, Kawamura et al., 2011; 7.6 PBq in the North Pacific through the end of April, Kobayashi et al., 2013; 28 PBq in the oceans through 20 April, Stohl et al., 2012). The present simulation used source data that were 1.65 times the direct discharge from 1FNPP of Tsumune et al. (2012) and 6.00 times the atmospheric deposition of Morino et al. (2011). Although the simple scaling resulted in decreasing discrepancy between observed and simulated seawater surface ^{137}Cs, we could not validate the ^{137}Cs inflow conditions in detail because neither the direct discharge nor the atmospheric deposition could be measured directly. We

attempted the validation by comparing between observed and simulated vertical sedimentary ^{137}Cs profiles but could not adequately at the present because of a lack of the available data (as in Sect. 3.3 of our manuscript). We will revise Sect. 2.2 in our manuscript as a below section Revise #2-2 to describe the aforementioned uncertainty of the atmospheric ^{137}Cs deposition. In addition, we will revise the other parts to describe quantitative uncertainty of our simulation related to the numerical condition of "ideal sediment property". Please refer to our response to RC C5124 of Reviewer #3 comment.

Referee #2 comment:

P. 12725, L. 16 Perhaps instead of "in spited of", "in spite of" will fit better.

Response:

We will revise it as the comment.

Revise #2-1: (Bold type shows revised sentences.)

(P. 12729 L1 – P. 12730 L6, Sect. 3.1)

3.1 Seawater ^{137}Cs dispersion

To investigate **performance** of the seawater ^{137}Cs model, simulated ^{137}Cs activities on the sea surface ($= C_{\mathrm{d}} + mC_{\mathrm{p}}$; however, the sea-surface mC_{p} was negligible) were compared with observed data. For this comparison, we used TEPCO monitoring data (TEPCO, 2011) at the nearshore sites shown in Fig. 4j, where time series were sufficient. Observations at stations W-1 and W-2 were within the same simulation grid (Fig. 4a and j), because they are very close.

Sea-surface ^{137}Cs simulated by our model **largely** agreed with observed data (Figs. 4

and S2). The average FA2 at all stations, which had a relatively large value of 52.2%, also indicates good model performance (Table S1). This agreement was **mainly** attributable to adjustment of the amount of ^{137}Cs inflow through atmosphere deposition and direct discharge from 1FNPP (mentioned in Sect. 2.3). However, all FB values in Table S1 became negative, indicating that the simulations still somewhat underestimated the sea-surface ^{137}Cs. **In particular, relatively large discrepancies between the simulations and the observations were found in initial period between the end of March and the mid-April (Fig. 4). These discrepancies would affect initial ^{137}Cs sedimentation in our simulation. Meanwhile, the results implied that the amount of actual ^{137}Cs inflow exceeded that input to our simulation.**

Spatiotemporal variation in sea-surface ^{137}Cs strongly depended on atmospheric deposition prior to the end of March, and afterward on direct discharge from 1FNPP (Figs. 3 and 4). Early in April, seawater ^{137}Cs reached a peak $O(10^3$–$10^4)$ Bq L^{-1} along the coast near 1FNPP (Fig. 4a–c) and $O(10^2)$ Bq L^{-1} 15 km offshore (Fig. 4d–i). There was a rapid decline of activity from mid-April to beginning of May, and a gradual decrease afterward (Fig. 4a–i). The decrease in seawater ^{137}Cs was caused by significant dispersion from the coastal region to the open ocean (Fig. S2). As mentioned in Sect. 1, many studies have discussed the spatiotemporal ^{137}Cs distribution and its physical background in detail **on the basis of numerical simulations** (Kawamura et al., 2011; Tsumune et al., 2012, 2013; Masumoto et al., 2012; Choi et al., 2013; Miyazawa et al., 2012, 2013). **Hence, we do not address the seawater ^{137}Cs in detail hereinafter. Although as a matter of course there was no earlier simulation that quite quantitatively agreed with our spatiotemporal distribution of the seawater ^{137}Cs because of differences in numerical procedures and/or simulation conditions, we confirmed that our seawater ^{137}Cs dispersion (Figs. 4 and S2) had similar qualitative features to the earlier simulations. For instance, our simulation tended to underestimate sea-surface ^{137}Cs southeast of 1FNPP such as at stations W-8–10 (Fig. 4g–i, and FB in Table S1) per the earlier simulations (Kawamura et al., 2011; Tsumune et al., 2012; Miyazawa et al., 2013).**

Revise #2-2: (Bold type shows revised sentences.)

(P. 12724, L1 – L29, Sect. 2.2)

Inflow conditions of the dissolved ^{137}Cs, particulate ^{137}Cs, and suspended particulate matter must be given at the sea-surface boundary in Eqs. (1)–(3), respectively. We considered the ^{137}Cs inflow through two pathways, direct discharge from 1FNPP and atmospheric deposition. We treated both inflow ^{137}Cs as in the dissolved phase. These source data were referred to Tsumune et al. (2012) for time series of direct discharge from 1FNPP **(total amount of 3.5 PBq until the end of May 2011)**, and Morino et al. (2011) for spatiotemporal variation in atmospheric deposition simulated by an atmospheric chemical-transport model **(total amount of 2.3/1.5 PBq in Region-1/2 through the end of April 2011)**. However, our preliminary experiments using these data indicated that simulated ^{137}Cs activities, **especially in surface seawater**, were **much** less than observed in all of Region-2, with the result that both sources were considered to be underestimated overall. **In fact, these amounts were much smaller than recent evaluation by Miyazawa et al. (2013) (the direct discharge: 5.5–5.9 PBq through 6 May 2011, the atmospheric deposition: 5.5–9.7 PBq within 12–62 and 108–180E through 6 May 2011). Although their estimation was based on comparison between seawater surface ^{137}Cs in their ocean-atmosphere simulations and that of field observations, their oceanic ^{137}Cs dispersion model did not include ^{137}Cs adsorption to suspended particulate matter and subsequent ^{137}Cs sinking in seawater. If the downward transport were not negligible, their estimation would become more. Furthermore, spatiotemporal variation of atmospheric ^{137}Cs deposition over the ocean, which has been estimated using numerical simulations by several previous studies besides Miyazawa et al. (2013) and Morino et al. (2011), included relatively large uncertainty and its total amount ranged very widely (e.g., 5 PBq within 30.5–48.0N, 127.0–154.5E through the end of April, Kawamura et al., 2011; 7.6 PBq in the North Pacific through the end of April, Kobayashi et al., 2013; 28 PBq in the oceans through 20 April, Stohl et al., 2012).**

This difference could be caused mainly by source parameter of ^{137}Cs emission from 1FNPP to atmosphere (e.g., 8.8 PBq, Terada et al., 2012; 13 PBq, Chino et al., 2011, 35.9 PBq, Stohl et al., 2012) and wet/dry deposition schemes (e.g., Stohl et al., 2012). The present simulation used source data that were **simply scaled as 1.65 times the direct discharge from 1FNPP of Tsumune et al. (2012) and 6.00 times the atmospheric deposition of Morino et al. (2011)** (Fig. 3a). As a result, the total direct discharge was 5.9 PBq through the end of May. Total atmospheric deposition on the sea surface was 13.8/9.2 PBq in Region-1/2 through the end of April. **Although the simple scaling resulted in decreasing discrepancy between observed and simulated seawater surface ^{137}Cs, we could not validate the ^{137}Cs inflow conditions in detail because neither the direct discharge nor the atmospheric deposition can be measured directly.**

We ignored ^{137}Cs loading from the land as a source because its amount, which has been estimated at 0.0075 PBq **of ^{134}Cs regarded as almost equivalent to ^{137}Cs amount** through the end of October 2011 (Otosaka and Kato, 2014), was much smaller than that of the direct discharge and atmospheric deposition. We also neglected particulate matter loading from the land, because of a lack of available data. This may impose some limitation on our simulation, because the validity of that neglect is not well known.

Reference (addition)

Chino, M., Nakayama, H., Nagai, H., Terada, H., Katata, G., and Yamazawa, H.: Preliminary estimation of release amounts of ^{131}I and ^{137}Cs accidentally discharged from the Fukushima daiichi nuclear power plant into the atmosphere, J. Nucl. Sci. Technol., 48, 1129–1134, 2011.

Kobayashi, T., Nagai, H., Chino, M., and Kawamura, H.: Source term estimation of atmospheric release due to the Fukushima Daiichi Nuclear Power Plant accident by

atmospheric and oceanic dispersion simulations, J. Nucl. Sci. Technol., 50, 255-264, doi:10.1080/00223131.2013.772449, 2013.

Stohl, A., Seibert, P., Wotawa, G., Arnold, D., Burkhart, J. F., Eckhardt, S., Tapia, C., Vargas, A., and Yasunari, T. J.: Xenon-133 and caesium-137 releases into the atmosphere from the Fukushima Dai-ichi nuclear power plant: determination of the source term, atmospheric dispersion, and deposition, Atmos. Chem. Phys., 12, 2313–2343, doi:10.5194/acp-12-2313-2012, 2012.

Terada, H., Katata, G., Chino, M., and H. Nagai: Atmospheric discharge and dispersion of radionuclides during the Fukushima Dai-ichi Nuclear Power Plant accident. Part II: verification of the source term and analysis of regional-scale atmospheric dispersion, J. Environ. Radioactiv., 112, 141–154, 2012.

A manuscript that we will revise has been uploaded in PDF format as supplement file.

Please also note the supplement to this comment:
http://www.biogeosciences-discuss.net/12/C6205/2015/bgd-12-C6205-2015-supplement.pdf

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