

Interactive comment on “Initial Spread of ¹³⁷Cs over the shelf of Japan: a study using the high-resolution global-coastal nesting ocean model” by Z. Lai et al.

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General Comments:

"Using numerical modeling, the author conducts a tracer experiment to simulate the CS-137 dispersion released from the Fukushima nuclear plant as a result of the 2011 Tohoku earthquake. By comparing with the circulation field generated by a coarser global model (Global-FVCOM), as well as observed CS-137 concentration at several near-shore and offshore stations, the author concludes that the high resolution model presented in this paper (JC-FVCOM) could better simulate the physical processes controlling the dispersal of CS-137. The expression of the article is clear and concise.

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However, I do not think this manuscript is acceptable at current stage mainly due to its lack of model skill assessment."

Answer: After the paper was submitted, we have significantly revised our manuscript to improve the synthesis of model-data comparison and model skill assessment. In particular, we have added the dynamical analysis and explanation based on the advection and dispersion theory to explain why a high-resolution model with better resolving of the geometry of FNPP is important to resolve the advection and dispersion processes in the ¹³⁷Cs spreading. We agree with the reviewer that the submitted version was not ready for publication and could easily lead to misunderstandings. We believe that the revised manuscript has taken the reviewer's comments into full consideration. To help the reviewer view what significant changes we have made in the revision, we included the revised manuscript as an attachment in our reply. Some details are briefly described below.

The abstract is completely rewritten, with focus on stating our new findings rather than arguing model methodology.

The Introduction is significantly modified by including 1) background oceanographic conditions of the study region, 2) detailed explanations of the key physical processes that control the passive tracer dispersion, and 3) reviews of previous observed and modeling assessment works that have been conducted for this topic.

The section "The model and design of numerical experiments" is rewritten with a detailed description of the model setup of various experiments and explanation of the difference between approaches used in our experiments and previous regional model assessment experiments.

The section "Results" were re-organized with inclusion of 1) comparison with observations and 2) comparison between high- and coarse-resolution models. The comparison was made with a more detailed explanation on dynamical processes that attribute to the simulation results, rather than simply show how good the simulation is in.

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To emphasize the dynamical aspects, we added an additional discussion section to provide a comprehensive explanation of the dynamics that are critically needed to improve the simulation and prediction of 137Cs. We also used dispersion theory to explain why a high-resolution model with geometric resolving of FNPP is so important to resolve the realistic advection and dispersion processes that control the 137Cs spreading from the FNPP.

Specific Comments:

"First of all, for any modeling effect, no matter it is physical oriented or a tracer/biogeochemical application, there should be model validation information regarding the model's capability of reproducing the circulation field. Surprisingly, there is not any such information presented. The cited "Chen et al. 2013" paper is only in "PREPARATION" status, which should not be used as model skill assessment."

Answer: We, an international research team with members from the University of Massachusetts-Dartmouth, Woods Hole Oceanographic Institution and Yokohama National University, have developed a high-resolution global-regional-coastal integrated seismic-ocean-tracer FVCOM model system to simulate the March 11 earthquake-induced tsunami, coastal inundation and initial spread of 137Cs. For the circulation, this model system consists of two nested models: 1) Global-FVCOM and 2) coastal FVCOM (in the text it is referred to as JC-FVCOM). Global-FVCOM has been validated through a 50-year spin-up simulation and a 33-year (1978-2010) hindcast assimilation (Gao et al., 2011; Hu et al., 2011, Chen et al., 2012). JC-FVCOM has been validated with a detailed comparison to the observed March 11 2011 tsunami and coastal inundation and satellite-derived regional near-surface circulation. Chen et al. (2013) was submitted earlier to Journal of Geophysical Research and now in the revision phase. Since the validation for the circulation was given in detail in Chen et al. (2013), we decided not to repeat it in this manuscript. Our studies in this manuscript were aimed at assessing the impact of multi-scale physical processes on the initial spread of 137Cs in the coastal region of Japan, thus building on the success of the simulation of the

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inundation and regional circulation described in Chen et al. (2013). The validation results were also presented in several conferences (Beardsley et al., 2012, Lai et al., 2012, Chen et al., 2012) and many invited talks.

"Secondly, the author spent a lot of context and figures to compare their high resolution version of model (JC-FVCOM) against the coarse resolution one (Global-FVCOM). There is no surprise that the high resolution model will generate some finer scale dynamics (e.g. eddies off the canal) that cannot be reproduced by a global model. However, without validation information, how can the author know that such small scale dynamics are true and are important for CS-137 dispersal on a large spatial scale?"

Answer: To help address this concern, we first added in this revision a detailed description of the different pathways taken by the 137Cs that leaked from the FNPP directly into the ocean for one major reason: to clearly identify the actual pathways of 137Cs that a) were used to design the high-resolution model grid used in JC-FVCOM and b) justify the need to resolve the geometry of the KNPP facility. (As noted in the response to reviewer 1), several reports clearly show that instead of through the two discharge canals, the majority of the 137Cs released to the ocean since April 2011 occurred was inside the KNPP seawall structure. The high-level radioactive water was mainly leaking from the Unit 2 and Unit 3 reactors during April through May, 2011, while the south discharge canal only contained the low-level waste water with a total amount of released 137Cs 2 - 4 orders of magnitude smaller (e.g. TEPCO press release on April 6 2011 posted at the web address: [http://www.tepco.co.jp/en/press/corpcom /release/11040601-e.html](http://www.tepco.co.jp/en/press/corpcom/release/11040601-e.html)). This press release clearly stated that the major releases of 137Cs from Unit 2 and Unit 3 reactors were at the intake channel of the units, which are located inside the seawall structure. Fig. 15 in Ohnishi (2012)'s review paper suggests that the leakage of highly contaminated water at the intake channel of Unit 2 actually started earlier even in March.

We then added detailed model-data comparisons for both the high- and coarse-resolution model simulations. Our results clearly show that the dispersion processes

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that control the initial ¹³⁷Cs spreading depend on model resolution and the advective and dispersive processes of the water exchange between the FNPP and coastal ocean. To our knowledge, all previous model assessments of the ¹³⁷Cs spreading were made with a regional-scale model without resolving the geometry of FNPP. Key questions here are: is the initial pumping process from FNPP critical for a model to produce a realistic spread of ¹³⁷Cs from the FNPP, or could the near-shore process be ignored if one is only interested to predict the ¹³⁷Cs spread over a regional scale? To address these questions, we followed the methods used in previous model assessments and tracked ¹³⁷Cs in the flow field predicted by Global-FVCOM.

In this regional model case, because the 2-km resolution grid was unable to resolve the FNPP facility and breakwater complex, the leaking ¹³⁷Cs was treated as a point source with the same rate of release used in the high-resolution model. The resulting spread of ¹³⁷Cs predicted by Global-FVCOM differed significantly from the high-resolution model case. It is clear that Global-FVCOM significantly overestimated the size of the plume. As a result, the model-computed ¹³⁷Cs concentrations were significantly lower than observations at both near-shore and offshore measurement sites.

The high- and coarse-resolution model results can help us understand why previous modeling efforts failed to reproduce the temporal variation of the ¹³⁷Cs concentration over the shelf region. Applying a 2-km resolution Regional Ocean Model System (ROMs) to the Japanese coast, Tsumune et al. (2012) conducted a tracer experiment to predict the ¹³⁷Cs spread over the shelf. The model did capture the ¹³⁷Cs concentration peak at MEXT-8 in mid-April, but significantly underestimated ¹³⁷Cs concentrations at the other MEXT-1 to MEXT-7 sites. Coincidentally, Estournel et al. (2012) reported that their model also underestimated ¹³⁷Cs concentrations at all MEXT sites, even though they increased the grid resolution to 600 m. They attributed this underestimation to the lack of information on the river discharge in the model which could cause a thin, low-salinity surface layer and enhance the offshore transport under the influence of wind. Our results, however, suggest that in order to reproduce the spread

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of ¹³⁷Cs over the shelf, a model needs to resolve the realistic coastal geometry of the FNPP and adjacent region. In order to reproduce the dispersion process from the leaking source to 1F-N and 1F-S, a model must be capable of resolving the complex small-scale vortex current field that controlled the water exchange or pumping around FNPP. Failure to capture this initial pumping process could lead to the unrealistic ¹³⁷Cs spreading over the shelf.

As we pointed out in the introduction, the spread of ¹³⁷Cs is controlled mainly by advection and dispersion processes. Chen et al. (2008) derived analytically the governing equations controlling the movement of the center of a small-scale dye patch in the coastal ocean. The equations indicate that after the dye is released, the movement of the dye patch is driven by the ensemble velocity integrated through the dye patch and the concentration flux related to the vertical shear of the horizontal velocity of the dye patch. Considering a dye patch that moves conservatively in the ocean, the total amount of the dye remains unchanged, but its concentration can change significantly as a result of deformation of the dye patch due to vertical and lateral dispersion that are related to velocity shears and turbulent diffusion. In order to capture the dye spreading, it is critical to resolve the realistic vertical and lateral diffusion processes. For many coastal ocean models, the horizontal diffusion is parameterized using a Smagorinsky eddy parameterization method (Smagorinsky, 1963), which depends on the model resolution and velocity shears. Our results indicate that an underestimation of ¹³⁷Cs concentration over the shelf predicted by Global-FVCOM was mainly due to the overestimation of ¹³⁷Cs spreading in the coastal region. This overestimation was caused by insufficient grid resolution to capture realistic lateral diffusion. This explanation can be applied to previous regional model simulations and emphasize the critical importance of model resolution in the parameterization of lateral diffusion.

"Thirdly, comparison of simulated and observed CS-137 concentration is not persuasive. Although the model reproduces the temporal changes (concentration peak followed by a dilution) of the CS-137 concentration around the power plant, the difference

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at the offshore stations (MEXT) is significant (fig.5 and 11, also pointed out by the other reviewer). The sediment absorption and releasing of CS-137 itself is of great scientific interests, however the discussion is not conclusive without analysis in conjunction with local oceanographic conditions."

Answer: See our answers for reviewer#1. We believe that these comparisons between simulated and observed 137Cs concentrations are reasonably good if one considers the unknown initial 137Cs distribution, the large uncertainty of spatial/temporal variations of the 137Cs loading from atmospheric deposition, point source, contaminated river inflow and non-point sources, as well as the complex process of absorption and releasing of 137Cs by sediments.

It is not a trivial task for a model to simulate and predict accurately the spatial distribution and temporal change of the 137Cs concentration off the Japan coast. Since advection and mixing are two key physical processes that control the spread of 137Cs in ocean waters, we need an ocean model that is capable of resolving an integrated coastal and regional circulation system over scales from a few meters (small scale, e.g. around FNPP) to a few kilometers (mesoscale) over the shelf. The flow around FNPP and near the coast is mainly controlled by tidal exchange, winds and local geometry. The circulation in this shelf region includes the Kuroshio on the south, the Oyashio Current on the north, Tsugaru Current from Tsugaru Strait, and multiple eddies formed in the intersection area of these currents. To simulate the outflow from FNPP, we need a model with accurate fitting of complex coastal geometry within and around FNPP. The water over the shelf was always stratified so that water temperature and salinity must be included in the model simulation. Several regional-scale ocean model exercises have been made to simulate the 137Cs spread from FNPP, e.g., Kawamura et al. (2011) and Tsumune et al. (2012) with a spatial resolution of 2 km or larger, and Estournel et al (2012) with a resolution of 0.6 km. However, the water exchange between FNPP and the surrounding ocean is through a ~200-m wide narrow entrance between the two breakwaters. The FNPP seawall structure between the two discharging canals

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(namely, the north and south discharging canals) is ~1300 m. Without sufficient resolution to accurately capture the complex discharge paths at FNPP, assessments made by these regional scale models could be biased with large uncertainty. It is not clear, however, to what degree this bias could be. Could the bias caused by model resolution and geometric fitting issues led to a significant different conclusion about the dispersion of 137Cs off the Japan coast or reproduce the same distribution with just a small difference in accuracy? To our knowledge, this issue has not been well addressed yet in previous modeling experiments

Our modeling results clearly demonstrated that the initial spread of 137Cs was controlled by the advective and lateral dispersive processes that not only depends on model grid resolution but geometric fitting. This explains why a high-resolution model with resolving geometry of FNPP was capable of improving the prediction of 137Cs at the MEXT sites. As the 137Cs plume spread into the stratified offshore region, in addition of vertical sedimentation process described above, the advection and vertical/lateral mixing becomes more critical. Our results indicate that an underestimation of 137Cs concentration over the shelf predicted by Global-FVCOM was mainly due to the overestimation of 137Cs spreading in the coastal region. This overestimation was caused by insufficient grid resolution to capture realistic lateral diffusion. This explanation can be applied to previous regional model simulations and emphasize the critical importance of model resolution in the parameterization of lateral diffusion. Therefore, the high-resolution does help improve the simulation of advection and dispersion processes that can directly affect the simulation accuracy of 137Cs concentration.

"At last, indicated by the other reviewer as well, more information of the inverse method is needed and the symbology and legend of figures 3,4,5,10,12,13, and 14 is not clear. In addition, there should be at least some background oceanographic condition of the study region in the introduction session."

Answer: See our replies to the reviewer's general comments given above. In the revision, we have included a detailed description of the inverse methods used in the

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experiments and also provided the background oceanographic condition of the study region in the introduction.

References:

Chen, C., R. Limeburner, G. Gao, Q. Xu, J. Qi, P. Xue, Z. Lai, H. Lin, R. Beardsley, B. Owens and B. Carlson (2012), FVCOM model estimate of the location of Air France 447, *Ocean Dynamics*, doi: 10.1007/s10236-012-0537-5

Gao, G., C. Chen, J. Qi and R.C. Beardsley (2011), An unstructured-grid, finite-volume sea ice model: development, validation and application, *J. Geophys. Res.*, 116, C00D04, doi: 10.1029/2010JC006688

Hu, S., C. Chen, R. Ji, D.W. Townsend, R. Tian, R.C. Beardsley and C.S. Davis (2011), Effects of surface forcing on interannual variability of the fall phytoplankton bloom in the Gulf of Maine revealed using a process-oriented model, *Mar. Ecol. Prog. Ser.*, 427, 29-49, doi: 10.3354/meps0904

Beardsley, R.C., C. Chen, Z. Lai, J. Sasaki, H. Lin, J. Lin, and R. Ji (2012), US-Japan Collaborative Research on the March 11, 2011 Earthquake, Tsunami Inundation, and Initial Spread of Fukushima Radionuclides into the Pacific Ocean, 2012 Ocean Sciences Meeting (abstract).

Chen, C., Z. Lai, R.C. Beardsley, H. Lin, J. Sasaki, J. Lin, and R. Ji (2012), Model Assessment of Inundation at the Fukushima Dai Nuclear Power Plant Facility and Initial Spread of Radionuclides in the Coast Ocean, 2012 Ocean Sciences Meeting (abstract).

Lai, Z., C. Chen, R.C. Beardsley, H. Lin, J. Sasaki, and J. Lin (2012), Model Assessment of 2011 Japan Tsunami and Coastal Inundation Processes, 2012 Ocean Sciences Meeting (abstract).

Chen, C., Lai, Z., Beardsley, R.C., Sasaki, J., Lin, J., Lin, H. and Ji, R. (2013), The March 11, 2011 Tohoku M9.0 Earthquake-induced Tsunami and Coastal Inundation

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along the Japanese Coast: A Model Assessment, *Journal of Geophysical Research*, in revision.

Please also note the supplement to this comment:

<http://www.biogeosciences-discuss.net/10/C1398/2013/bgd-10-C1398-2013-supplement.pdf>

Interactive comment on *Biogeosciences Discuss.*, 10, 1929, 2013.