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Initial Spread of ^{137}Cs over the shelf of Japan: a study using the high-resolution global-coastal nesting ocean model

Z. Lai[1,2], C. Chen[2], R. Beardsley[3], H. Lin[2], R. Ji[4], J. Sasaki[5], and J. Lin[6]

[1]School of Marine Sciences, Sun Yat-Sen University, Guangzhou, China
[2]School for Marine Science and Technology, University of Massachusetts-Dartmouth, New Bedford, MA 02744, USA
[3]Department of Physical Oceanography, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA
[4]Biology Department, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA
[5]Department of Civil Engineering, Institute of Urban Innovation, Yokohama National University, Hodogayaku, Yokohama 240-8501, Japan
[6]Department of Geology & Geophysics, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA

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Correspondence to: Z. Lai (laizhig@mail.sysu.edu.cn)

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Abstract

The 2011 Tohoku earthquake caused radionuclide ^{137}Cs be directly released into the ocean from the Fukushima Dai-ichi nuclear power plants. A high-resolution global-coastal nesting ocean model was established to simulate the initial spread of ^{137}Cs as conservative tracer over the shelf of Japan after the accident. The major advantage in the current model system is to use unstructured grids to resolve the power plant and the coastal geometry with a grid resolution much higher than that used in previous modeling experiments. Therefore, it gives us an opportunity to examine the necessity whether the detailed structure of the Power plant should be considered for numerical experiment of ^{137}Cs dispersion or not. This could provide us an alternative insight into the physical processes that lead to its spread of ^{137}Cs over the shelf of Japan. Our results suggested that to resolve the dispersion process from the source point to the south and north discharging canal is critical for an accurate prediction of the spread of ^{137}Cs to the 30 km sites off the coast. Moreover, a 2 km grid resolution along Japan coast is probably not high enough to resolve the plume correctly. Finally, the model-data comparison suggested that the physical process associated with the transfer of dissolved ^{137}Cs into the sediment phase could potentially be important and should be considered in the future tracer modeling.

1 Introduction

The magnitude 9.0 Tohoku earthquake caused a massive tsunami which reached 16 m in wave height nearshore and devastated the east coast of Japan on 11 March 2011. In this catastrophe, the Fukushima Dai-ichi nuclear power plants (FNPP1) was seriously damaged resulting in the release of large amount of artificial radionuclide, mainly ^{131}I ($t_{1/2}$ = 8.02 days), ^{134}Cs ($t_{1/2}$ = 2.065 yr) and ^{137}Cs ($t_{1/2}$ = 30.07 yr) from several reactor units into the environment in the following months (Ohnishi, 2012). Unlike the Chernobyl nuclear plant accident which occurred at a site far from the ocean, the FNNP1

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is located on the coast. Therefore, lots of radio-contaminated waters were directly discharged or leaked into the ocean from the power plant. Other sources of radionuclides into the ocean include the wet and dry deposition of part of the release to the atmosphere (Honda et al., 2012) and polluted river discharge from land (Oura and Ebihara, 2012). Among those released isotopes, ^{137}Cs is of particular interest because it has a very long half-time and its accumulation in marine food chains could exert profound impact on marine biota and human (Buesseler et al., 2011; Grossman 2011). Motivated by this, numerical experiments were conducted by various research groups in an effort to understand the dispersion of ^{137}Cs off Japan coast to the interior of Pacific Ocean (see for example, Behrens et al., 2012; Dietze and Kriest, 2012).

However, to make an accurate predict of the spatial/temporal distributions of ^{137}Cs concentration off the Japan coast is not a trivial task. This is due to the uncertainty of our knowledge on the source term namely the total amount of isotopes released into the ocean and its time-dependence (Estournel et al., 2012). A usual approach to work out this problem requires inversely determine the source amount by tracking a unit conservative tracers (dye) in the current field for a relatively short period (valid for slow decaying radioactive isotope such as ^{137}Cs) and finding out its time-varying magnitude such that the predicted tracer field would match the observations as closely as possible. This method has been used to evaluate the total amount of ^{137}Cs directly released into the ocean from FNPP1 (Kawamura et al., 2011; Tsumune et al., 2012; Estournel et al., 2012).

Noticeably, a prerequisite of the method is that the predicted current field should be a good representation for the coastal dynamics and the regional mesoscale circulation. Ideally this would requires realistic forcings data to be used in the ocean circulation model with a well-designed mesh capable of depicting the complex coastal geometry and resolving the multi-scale dynamics ranging from the nearshore structure to the coastal and mesoscale systems. To the best of our knowledge, however, all the ocean models currently used to inversely determine the source term of ^{137}Cs into the ocean from the FNPP1 are based on horizontal structured grid models with a spatial

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resolution no less than 2 km (Kawamura et al., 2011; Tsumune et al., 2012), except that of 600 m in Estournel et al. (2012). Since the size of the FNPP1 delimited by the distance between the north and south discharging canal is only about 1300 m, such a grid configuration obviously could not resolve the reality of the situation as radioactive materials were directly released inside the breakwater of the power plant and dispersed into the coast by exchanging waters with the ocean through a less than 200 m wide narrow entrance. As a result, it is not clear to what degree this simplication of geometric representation in models could affect the accuracy of this method.

In addition, all the numerical experiments assumed that ^{137}Cs was in dissolved form without interacting with the suspended matter. As pointed out by Estournel et al. (2012), such a hypothesis could result in an overestimation of the predicted ^{137}Cs concentration by ignoring a possible sinking term. This error might be particularly significant in the coastal zone where the concentration of suspended matter should be potentially high. Moreover, the situation would become more complicated if one considers the continued release of ^{137}Cs from coastal sediments that close to the FNPP1 and might absorb lots of ^{137}Cs after the disaster. This can be inferred since the observation data showed that the concentration of radioactive materials through the end of July remains higher than expected in the coastal region (Buesseler et al., 2011).

Recently, an Japan tsunami and inundation model was established aiming to provide a highly accurate simulation of the tsunami process and associated coastal inundation on 11 March 2011 (Chen et al., 2013). It used realistic boundary conditions through nesting with a state-of-art global ocean model. Using unstructured grid, the model has a very high local grid resolution to resolve the detailed structure of the FNPP1, such that the multi-scale wave propagation from the regional scale down to the power plant scale can easily be resolved. Based on that, a tracer study was conducted in the current paper with a focus to understand the necessity whether the detailed structure of the power plant should be considered for numerical experiment of ^{137}Cs dispersion or not. This could benefit us by providing an alternative insight into the important physical processes that lead to its spread of ^{137}Cs over the shelf of Japan.

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2 Description of numerical experiment

2.1 Tracer model system for ^{137}Cs

A FVCOM tracer model is used in the current study based on a global-regional-coastal nested system (hereafter referred to as the global-Japan coastal nested FVCOM system) (Fig. 1). Detailed descriptions of FVCOM ocean circulation model can be found in a series of literatures (Chen et al., 2003, 2006a,b) and the validation of the tracer model was described in a model-dye comparison experiment (Chen et al., 2008). For the current study, the global-Japan coastal nested FVCOM system includes a FVCOM global ocean model (Global-FVCOM) and a high-resolution Japan coastal FVCOM (JC-FVCOM). This model framework has been successfully applied to simulate the March 2011 tsunami process and resultant coastal inundation (Chen et al., 2013). These models are nested through a common boundary where the triangle cells from both models match exactly. The Global-FVCOM has a grid resolution about 2 km along the east Japan coast resemble to those used in the rectangle grid models. The JC-FVCOM is designed to resolve the FNPP1 and the coast geometry with a high grid resolution only tens of meters. Vertically, the model has a total of 45 layers with non-uniform layer thickness that features 10 and 5 uniform thin layers near the surface and bottom (s-coordinate) and transit to a vertical uniform grid (sigma-coordinate) in the shallow continental and coastal regions at 225 m water depth. The Global FVCOM is driven by astronomical tidal forcing with eight constituents and NCEP reanalysis data for surface wind stress, shortwave irradiation, net heat flux, air pressure, precipitation and evaporation starting from 1 January 2011. In additions, satellite products of GHRSST Sea Surface Temperature (http://www.nodc.noaa.gov/SatelliteData/ghrsst) and AVISO Sea Surface Height (http://www.aviso.oceanobs.com/en/data/products/sea-surface-height-products.html) were assimilated into the model to create the boundary conditions that represent the "best fit" of the reality. The JC-FVCOM was then driven to output the hourly current field for the tracer model. In order

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to compare the results with and without considering the FNPP1, the same tracer simulation was conducted using both JC-FVCOM and global-FVCOM.

2.2 Determination of the source term of ^{137}Cs

A major uncertainty in simulating the spread of ^{137}Cs lies in the source term (Tsumune et al., 2012; Estournel et al., 2012). Following a similar approach (Tsumune et al., 2012), we inversely determined the source term that directly released into the ocean by simply tuning it in the period from 26 March to 10 April unless the predicted time series of tracer concentrations match the observation data at the north discharging canal (1F-N) and the south discharging canal (1F-S) of the FNPP1 closely (Fig. 2). Then, the predicted tracer field was validated by comparing the model results with the observation data at eight MEXT (Japan Ministry of Education, Culture, Sports, Science and Technology) sites 30 km off the coast.

It should be noted that a more accurate practice would require incorporating the atmosphere tracer model since part of the ^{137}Cs released into the atmosphere entered into the ocean through the wet/dry deposition. As shown by Kawamura et al. (2011), without considering the atmospheric deposition the ocean tracer model will tend to underestimate the predicted concentrations of radionuclides at some coastal observation site.

However, atmospheric dispersion model may not necessarily be considered in the current study for two reasons. Firstly, we do not intend to provide a more accurate estimate of ^{137}Cs released into the ocean. So, the source term here simply represents the "best guess" which allow us to validate the tracer model. Secondly, the focus of this paper is to understand the importance of resolving the detailed structure of the FNPP1 in the tracer experiment. Whether it will improve our simulation or not and to what degree? Obviously, that would require evaluating the model's performance through a more thorough model-data comparison. Therefore, as shown in Fig. 3, a comprehensive dataset was collected in the current study to include all the available observation data collected by MEXT, TEPCO (Toyko Electric Power Company, the power plant operator)

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and WHOI (Woods Hole Institute of Oceanography, kindly provided by Ken Buesseler). In addition, our tracer release started from 26 March 2011 based on the research done by Tsumune et al. (2012). Considering that the influence of atmospheric deposition on ^{137}Cs concentration in the ocean largely stopped by the end of March when the direct release into the ocean became significant afterward (Kawamura et al., 2011; Tsumune et al., 2012), it should also be valid to ignore the atmospheric deposition in the current study with a minimum effect on the final discussion.

3 Results

Figure 4 shows the JC-FVCOM model predicted ^{137}Cs concentration at station 1F-N and 1F-S after tuning the source term. It should be emphasized here although this is the result under adjustment it still certainly reflect some of the reality because the current field determines how the released ^{137}Cs can be transported to these sample sites thus part of the observed temporal variations. On the contrary, such a variation for example shown by Estournel et al. (2012) was essentially under the control of the temporal variations of the source term because their model grid simply does not high enough to distinguish between the discharging point and the 1F-N and 1F-S.

A further validation of the inversely determined source term was done by comparing the model predicted ^{137}Cs concentration at eight MEXT sites (Fig. 5). It suggests that ^{137}Cs can be detected at 30 km location off the coast about two weeks after the direct release into ocean. The peak concentration (~ 100 Bq L) occurs at the end of April and quickly decreases to below detection limit at early May and then continues decrease afterwards. The model predicted results agreed reasonably well with the observation in both magnitude and variations. The ^{137}Cs concentration detected before 8 April in these sites was suspected to be the results of atmospheric deposition. Since neither the atmospheric deposition nor the initial ^{137}Cs distribution at 26 March was considered in the current study, it thus not possible to validate the model results for that period. This result is superior to that shown by Estournel et al. (2012) and Tsumune et al. (2012),

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whose predictions show a much lower concentration than observations. We will return to this point in the discussion.

The dispersion of ^{137}Cs into the ocean was determined by the along shore coastal flow as well as the FNPP1 controlled current structure. As shown in Fig. 6, ^{137}Cs was pumped into the coast through a narrow entrance of the two embankments. Because the outflow through the entrance is so strong ($\sim 2\,m\,s^{-1}$), it can generate a cyclonic eddy at the mouth of the entrance which transport the ^{137}Cs to the 1F-N site only taking about a couple of hours. At the same time, the southward along shore coastal current passing the structure can cause a weak anti-cyclonic eddy similar to the headland effect, which could enhance the cross isobaths dispersion. Comparing the initial release of ^{137}Cs in JC-FVCOM and Global-FVCOM for example on 26 March, 04:00 UTC it is clear that Global-FVCOM significantly overestimate the size of the plume thus the concentration in the predicted plume will be expected to be lower (Fig. 7).

The initial spread of ^{137}Cs over the shelf of Japan shows a strong south-north movement under the influence of wind (Fig. 8). Before June, the ^{137}Cs plume was mainly constrained within the coast and transport southward. It could reach to its maximum extend about 180 km south of the FNPP1 around June where some of the ^{137}Cs will be carried away by the Kuroshio current system. At the same time, the northward wind caused coastal upwelling and started to disperse the ^{137}Cs plume offshore. These results were consistent with the sampling records at Hasaki, a coastal station 180 km south of the FNPP1 (Aoyama et al., 2012) as well as the results of numerical simulations (Kawamura et al., 2011; Estournel et al., 2012). In July and August, the plume was predominantly transported toward the north and gradually dispersed into the interior of Pacific Ocean. The records from 10 sites along the coastline of the Northern Sanriku and Tsugaru Strait north of the FNPP1 in May-June 2011 found little increase of ^{137}Cs activity as a result of the accident (Inoue et al., 2012). This also can be confirmed in our simulations. Comparing the results in JC-FVCOM and Global-FVCOM at the beginning of June, however, it shows that in the Global-FVCOM run, there is significantly northward extension of the ^{137}Cs plume to those regions, which seems not real (Fig. 9).

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A more thorough validation of the model results was shown in Fig. 10 for all the collected surface ^{137}Cs observation data. It shows that for TEPCO data which are located most close to the FNPP1, the model is able to make a reasonable good prediction. The model predicted plume also matches the MEXT data well that are further offshore than the TEPCO data and are mainly located within the 30 km distance off the coast. The mismatch found between the model and the observation by the end of March and at early April again is due to the ignoring of atmospheric deposition, so it is not possible to validate the model results for that period. However, the model tends to overestimate the WHOI data that observed at June and the MEXT data by the end of August. By visually comparing the horizontal view between JC-FVCOM results and WHOI data, it becomes clear that although the model makes a good prediction for those deep basin stations, it tends to overestimate the magnitude and size of the plume for the coastal area (Fig. 11)

4 Discussion and conclusion

Using a 2 km grid resolution Regional Ocean Model System (ROMs) for Japan coast, Tsumune et al. (2012) showed that their model failed to reproduce the observed temporal variation of ^{137}Cs concentration at the eight MEXT sites 30 km off the FNPP1. Although their simulation was able to catch the peak at site 8 in mid-April, the results at other seven sites have been significantly underestimated. They suggested that this was what the model needed to be improved further (Tsumune et al., 2012). Coincidentally, Estournel et al. (2012) also found their model significantly underestimate those observations at 30 km offshore, even though their grid size has reduced to 600 m. They attributed this to the lack of information on the discharge of rivers in the model which was suspected to cause a thin, low-salinity surface layer and facilitate the offshore transport under the influence of wind. In contrast, our model shows a much better comparison at these sites. In our opinion, this should be attributed to a better resolution of the coastal geometry and structures. By resolving the dispersion process from

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the source point to 1F-N and 1F-S, it essentially provides us a better estimation of the source term and a highly resolved current field, which is critical for the spread of ^{137}Cs under complicated coastal dynamical environment. Therefore, this could be an important implication for further tracer modeling study. Besides, our comparison of results between JC-FVCOM and Global-FVCOM suggest that 2 km grid resolution along Japan coast is not high enough to resolve the plume correctly.

The model-data comparison suggested that after June, the JC-FVCOM tends to overestimate the surface ^{137}Cs concentration at coastal region, even though the model's prediction is still pretty good for the near shore area (mainly TEPCO data). A reasonable explanation for that could be the model misses some exit mechanism for ^{137}Cs in seawater or a degradation term. However, considering that ^{137}Cs essentially behaves as dissolved conservative tracer in seawater without decaying for short period, the only possibility is that ^{137}Cs is transferred out of the water column into the sediment through biotic and abiotic particles absorption. To support this hypothesis, the near bottom ^{137}Cs records are compared with the model data. As shown in Fig. 12, contrary to the surface result, the model tends to underestimate the ^{137}Cs concentration near bottom. This opposite results between the surface data and bottom data indicates that a downward flux of ^{137}Cs should be defined in the model such as a sinking term to compensate the model-data discrepancy. Actually, by plotting the time series of sediment records for ^{137}Cs in Fig. 13–14, we found there was a large increase in ^{137}Cs concentration in sediments before June restricted in the along shore area delimited by the 100 m isobaths around the FNPP1. A simple calculation shows that during the period of April-June, the magnitude of model-data discrepancy for the surface and bottom data is about 48 % and −39 % for the coastal area with active ^{137}Cs deposition into sediment around FNPP1. Assuming that the ^{137}Cs concentration is vertically uniform distributed in the shelf region, this gives a rough estimate about 9 % of the total amount of ^{137}Cs in the seawater could be transformed into the sediments during the out spreading. However, such an estimate is rather roughly and could vary significantly under many uncertainties.

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References

Aoyama, M., Tsumune, D., Uematsu, M., Kondo, F., and Hamajima, Y.: Temporal variation of ^{134}Cs and ^{137}Cs activities in surface water at stations along the coastline near the Fukushima Dai-ichi Nuclear Power Plant accident site, Japan, Geochem. J., 46, 321–325, 2012.

Behrens, E., Schwarzkopf, F. U., Lübbecke J. F., and Böning, C. W.: Model simulations on the long-term dispersal of ^{137}Cs released into the Pacific Ocean off Fukushima, Environ. Res. Lett., 7, 034004, doi:10.1088/1748-9326/7/3/034004, 2012.

Buesseler, K., Aoyama, M., and Fukasawa, M.: Impacts of the Fukushima nuclear power plants on marine radioactivity, Environ. Sci. Tech., 45, 9931–9935, 2011.

Chen, C., Liu H., and Beardsley R.: An unstructured grid, finite-volume, three dimensional, primitive equations ocean model: application to coastal ocean and estuaries, J. Atmos. Ocean Tech., 20, 159–186, 2003.

Chen, C., Beardsley R. C., and Cowles G.: An unstructured grid, finite-volume coastal ocean model (FVCOM) system, Special Issue entitled "Advances in Computational Oceanography", Oceanography, 19, 78–89, 2006a.

Chen, C., Cowles G., and Beardsley R. C.: An Unstructured Grid, Finite-Volume Coastal Ocean Model: FVCOM User Manual Second Edition, SMAST/UMASSD Technical Report-06-0602, 315 pp., 2006b.

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Chen, C., Xu Q., Houghton R., and Beardsley R. C.: A model-dye comparison experiment in the tidal mixing front zone on the southern flank of Georges Bank, J. Geophys. Res., 113, C02005, doi:10.1029/2007JC004106, 2008.

Chen, C., Lai, Z., Beardsley, R. C., Sasaki, J., Lin, J., Lin, H., and Ji, R.: The March 11, 2011 Tōhoku M9.0 earthquake-induced Tsunami and coastal inundation along the Japanese coast: a model assessment, J. Geophys. Res., in preparation, 2013.

Dietze, H. and Kriest, I.: ^{137}Cs off Fukushima Dai-ichi, Japan – model based estimates of dilution and fate, Ocean. Sci., 8, 319–332, 2012.

Estournel, C., Bosc E., Bocquet, M., Ulses, C., Marsaleix, P., Winiarek, V., Osvath, I., Nguyen, C., Duhaut, T., Lyard, F., Michaud, H., and Auchair, F.: Assessment of the amount of cesium-137 released into the Pacific Ocean after the Fukushima accident and analysis of its dispersion in Japanese coastal waters, J. Geophys. Res., 117, C11014, doi:10.1029/2012JC007933, 2012.

Grossman, E.: Radioactivity in the Ocean: Diluted, But Far from Harmless, available at: http://e360.yale.edu/feature/radioactivity_in_the_ocean_diluted_but_far_from_harmless/2391/, last access: December 2012.

Honda, M. C. H., Aono, T., Aoyama, M., Hamajima Y., Kawakami, H., Kitamura M., Masumoto Y., Miyazawa Y., Takigawa M., and Saino, T: Dispersion of artificial caesium-134 and -137 in the western North Pacific one month after the Fukushima accident, Geochem. J., 46, 1–9, 2012.

Inoue, M., Kofuji, H., Hamajima, Y., Nagao, S., Yoshida, K., and Yamamoto, M.: ^{134}Cs and ^{137}Cs activities in coastal seawater along Northern Sanriku and Tsugaru Strait, northeastern Japan, after Fukushima Dai-ichi nuclear power plant accident, J. Environ. Radioact., 111, 116–119, 2012.

Kawamura, H., Kobayashi, T., Furuno, A., In, T., Ishikawa, Y., Nakayama, T., Shima, S., and Awaji T.: Preliminary numerical experiments on oceanic dispersion of ^{131}I and ^{137}Cs discharged into the ocean because of the Fukushima Daiichi nuclear power plant disaster, J. Nucl. Sci. Tech., 48, 11, 1349–1356, 2011.

Ohnishi, T.: The disaster at Japan's Fukushima-Daiichi nuclear power plant after the March 11, 2011 Earthquake and Tsunami, and the resulting spread of radioisotope contamination, Radiat. Res., 177, 1–14, 2012.

Oura, Y. and Ebihara, M.: Radioactivity concentrations of ^{131}I, ^{134}Cs and ^{137}Cs in river water in the Greater Tokyo Metropolitan area after the Fukushima Daiichi nuclear power plant accident, Geochem. J., 46, 303–309, 2012.

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Tsumune, D., Tsubono, T., Aoyama, M., and Hirose, K.: Distribution of oceanic ^{137}Cs from the Fukushima Daiichi nuclear power plant simulated numerically by a regional ocean model, J. Environ. Radioact., 111, 100–108, 2012.

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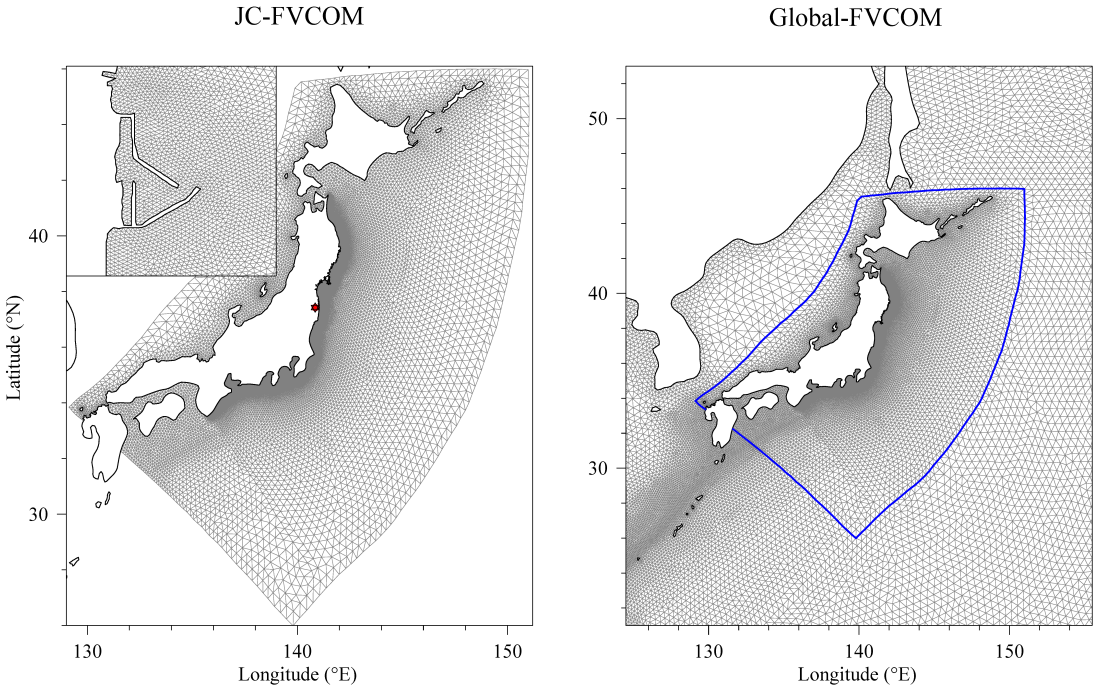

Fig. 1. Model grids for the global-Japan coastal nested FVCOM system. The blue line indicate the location of common boundary.

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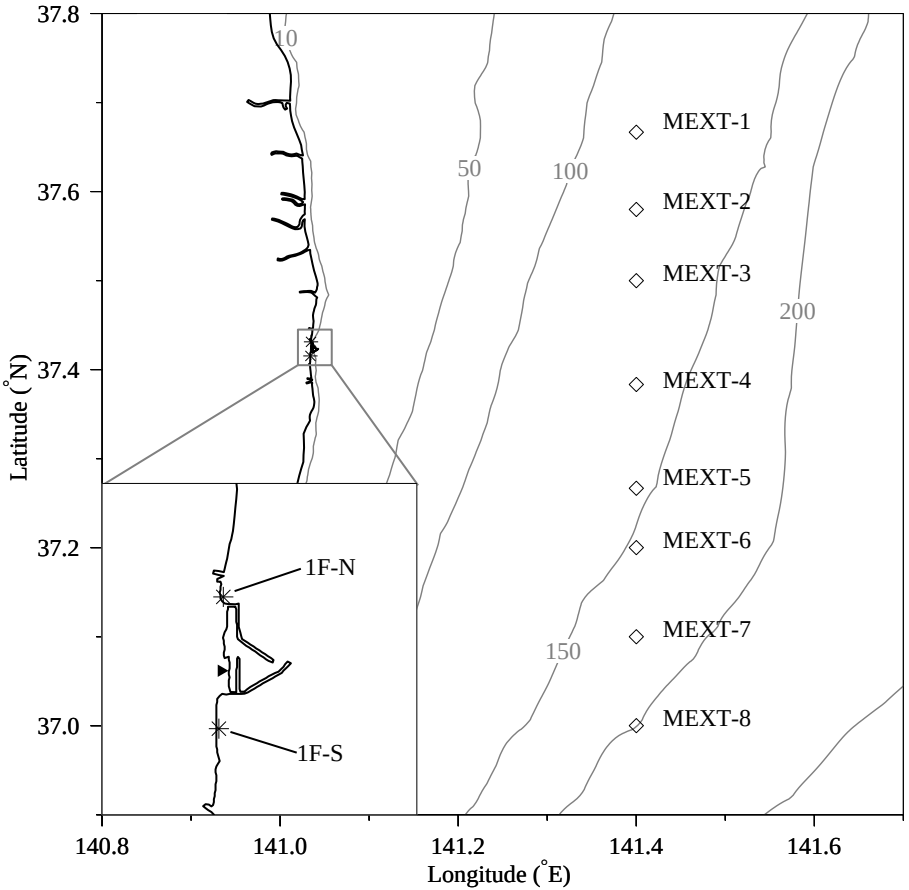

Fig. 2. Locations of the north discharging canal (1F-N) and the south discharging canal (1F-S) and the eight MEXT sampling sites 30 km off the coast. The filled-triangle-right indicates the location of discharging point.

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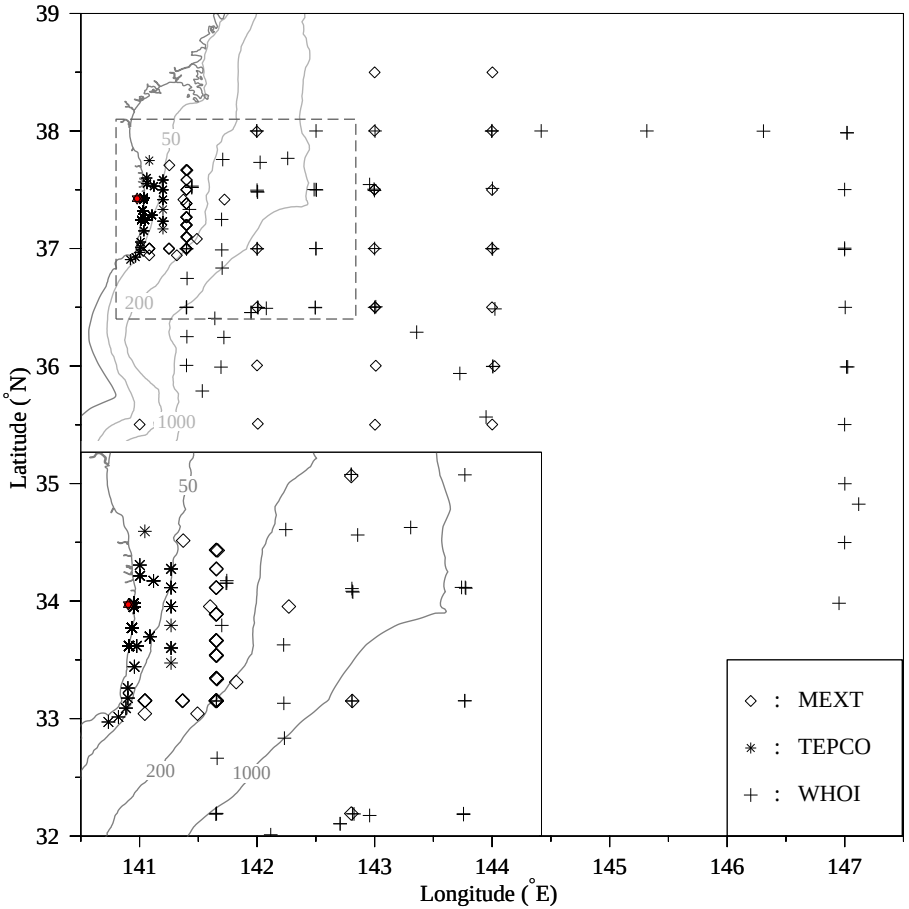

Fig. 3. Locations for all the collected observation data.

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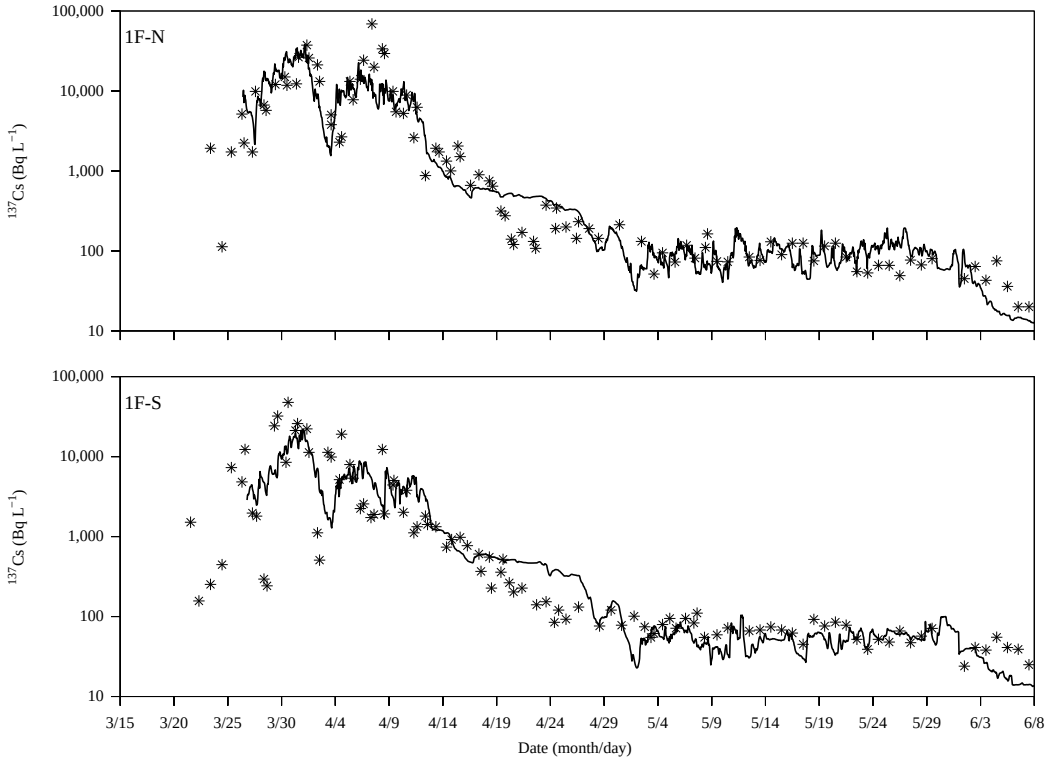

Fig. 4. Time series of model data comparisons at 1F-N and 1F-S.

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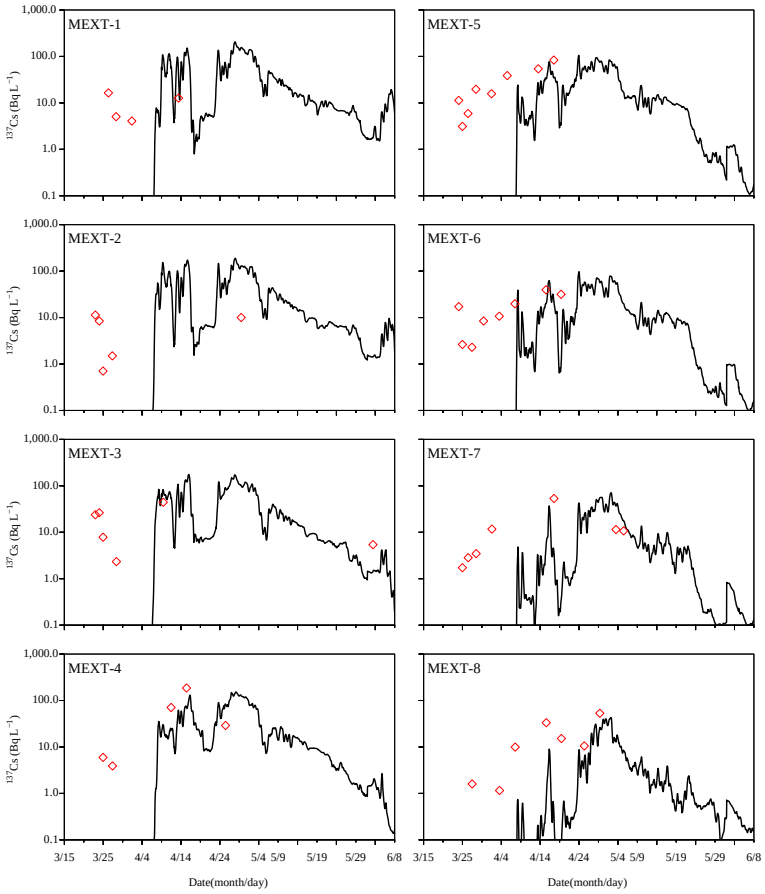

Fig. 5. Times series of Model data comparisons at eight MEXT sampling sites 30 km off the coast.

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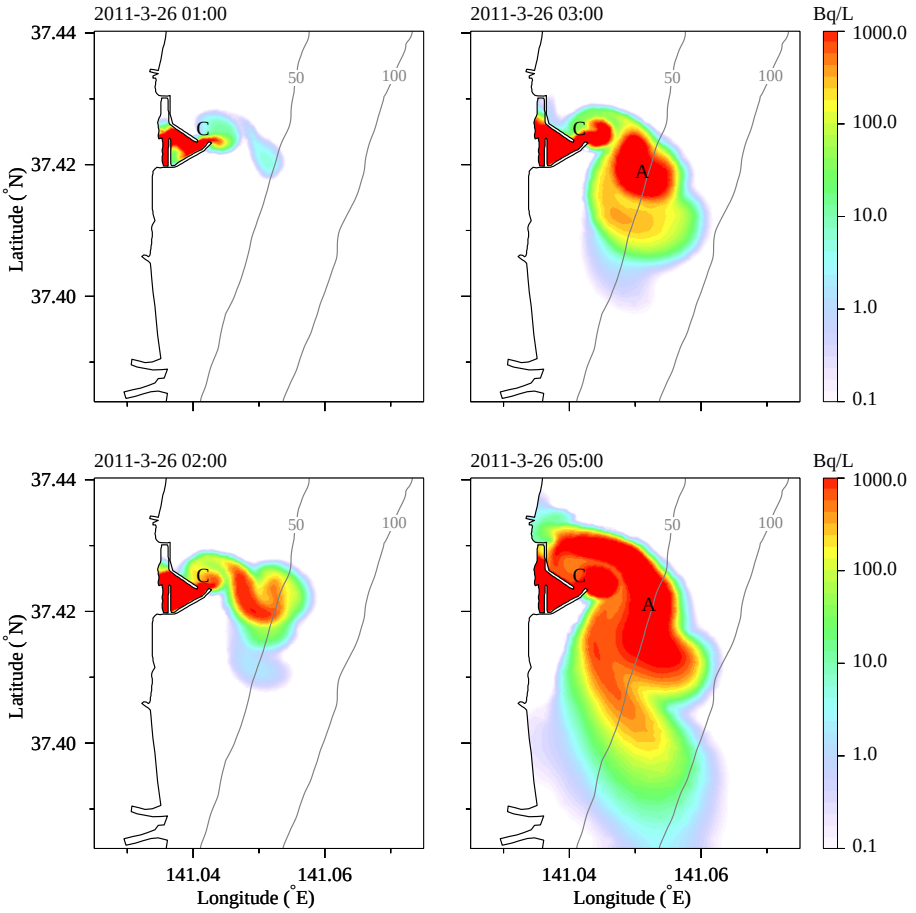

Fig. 6. The initial dispersion of ^{137}Cs from the power plant into the coast. C: indicates the location of a cyclonic eddy; A: indicates the location of an anti-cyclonic eddy.

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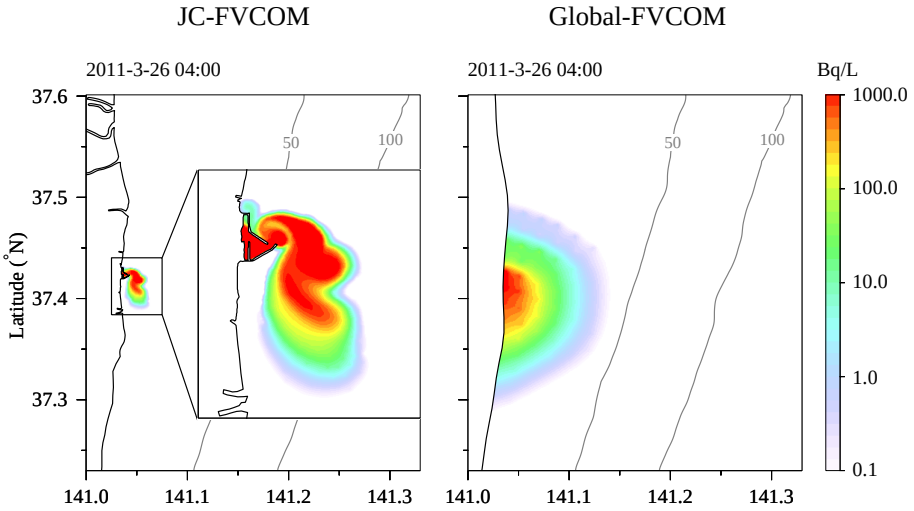

Fig. 7. Comparison of the initial dispersion of ^{137}Cs between JC-FVCOM and Global-FVCOM.

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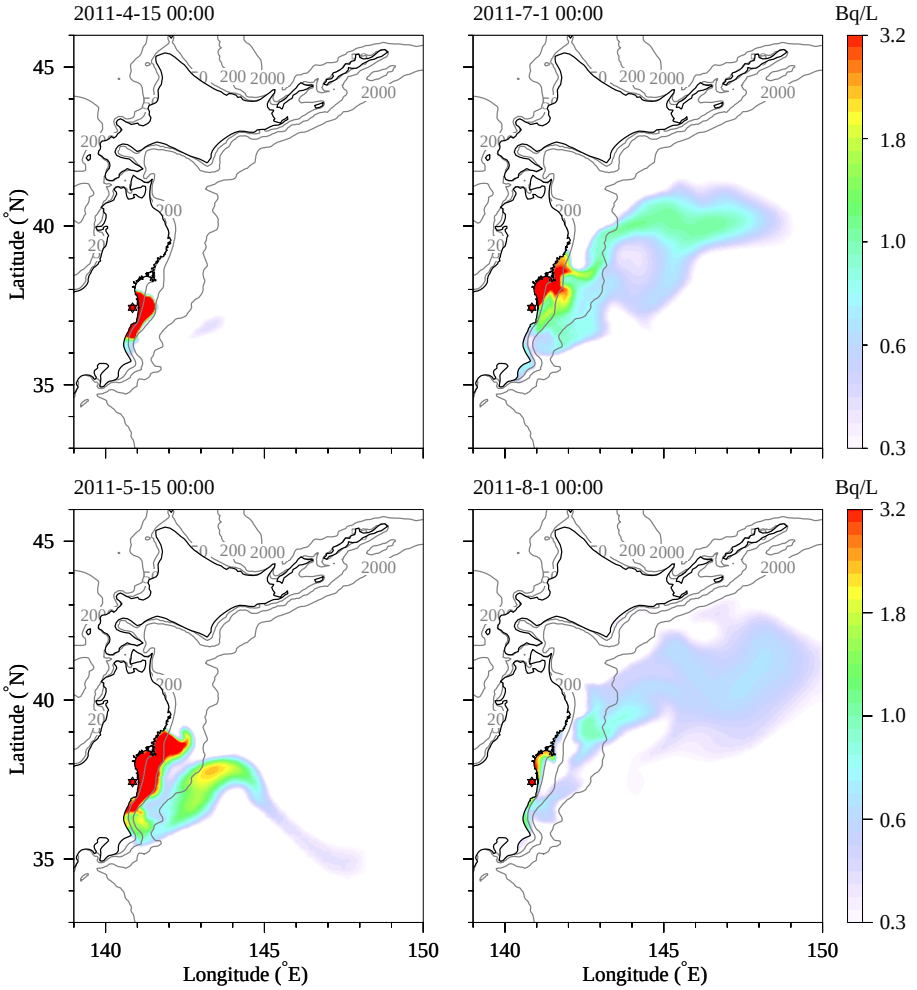

Fig. 8. Initial spread of ^{137}Cs off the shelf of Japan in JC-FVCOM.

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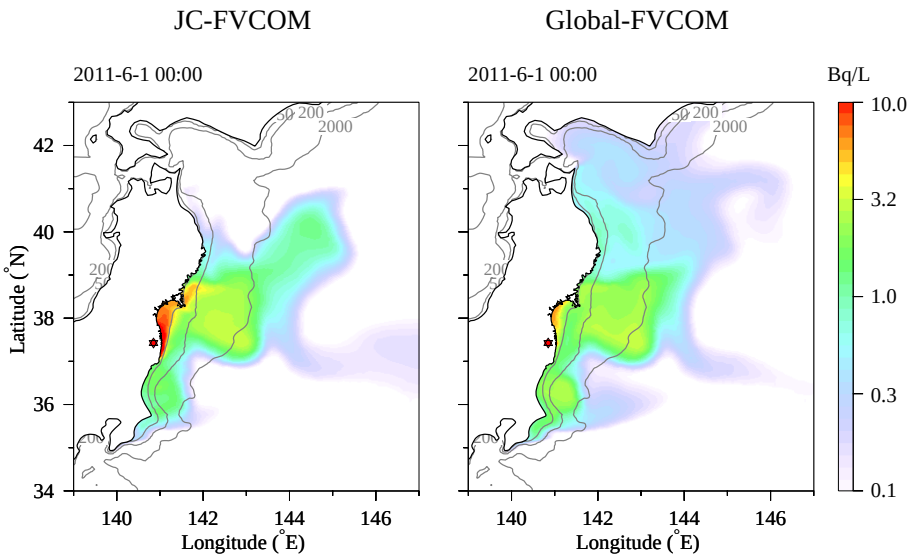

Fig. 9. Comparison of the spread of ^{137}Cs at 1 June between JC-FVCOM and Global-FVCOM.

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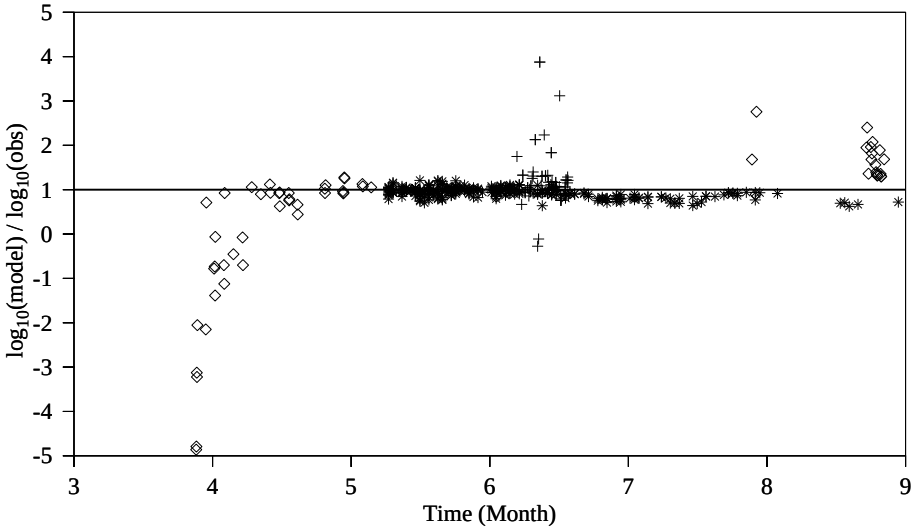

Fig. 10. Time series of model-data comparison for surface ^{137}Cs results.

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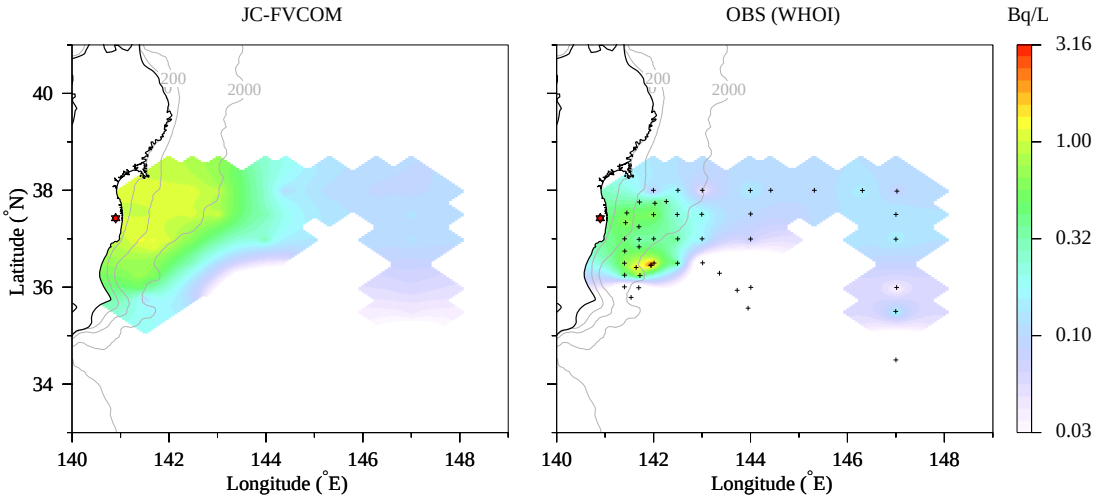

Fig. 11. Comparison of the Plan view of the surface ^{137}Cs at the sample locations between JC-FVCOM and WHOI data.

BGD
10, 1929–1955, 2013

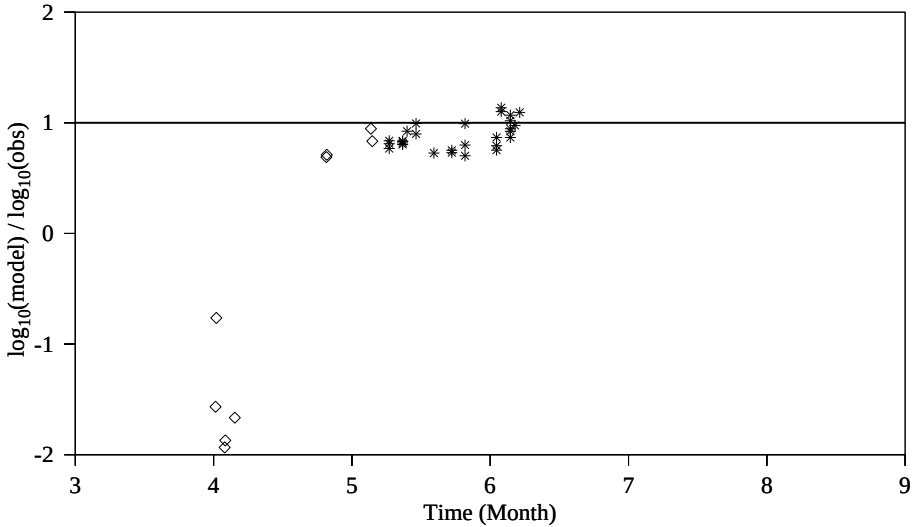

Fig. 12. Time series of model-data comparison for near-bottom ^{137}Cs results.

BGD
10, 1929–1955, 2013

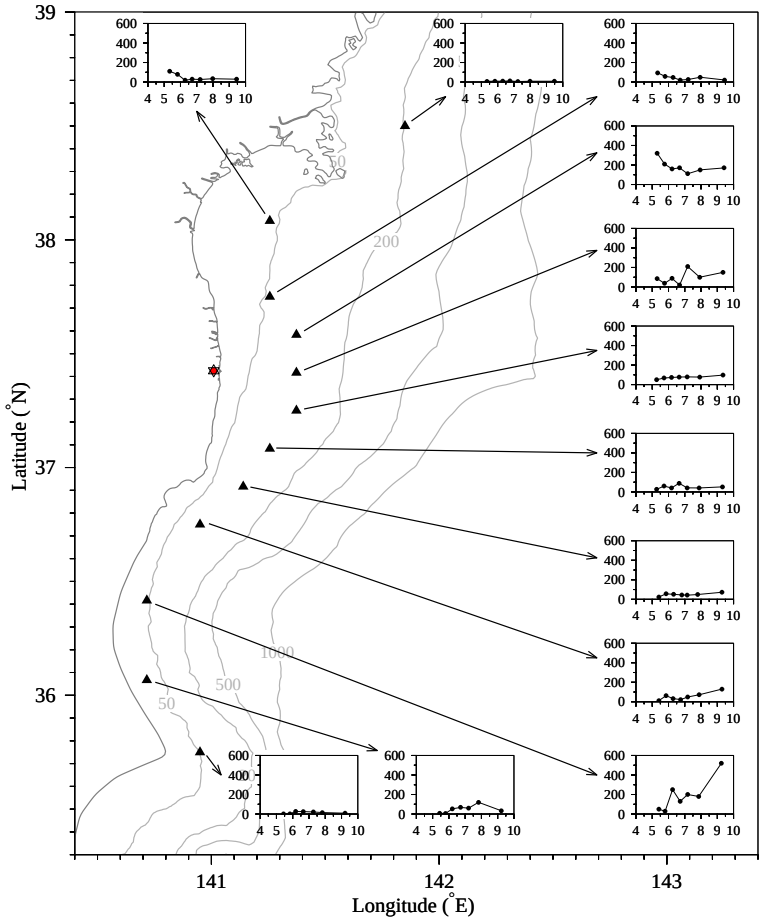

Fig. 13. Spatial and temporal distribution of ^{137}Cs concentration in sediments in the outer-shelf area. The data unit is Bq kg^{-1}.

BGD
10, 1929–1955, 2013

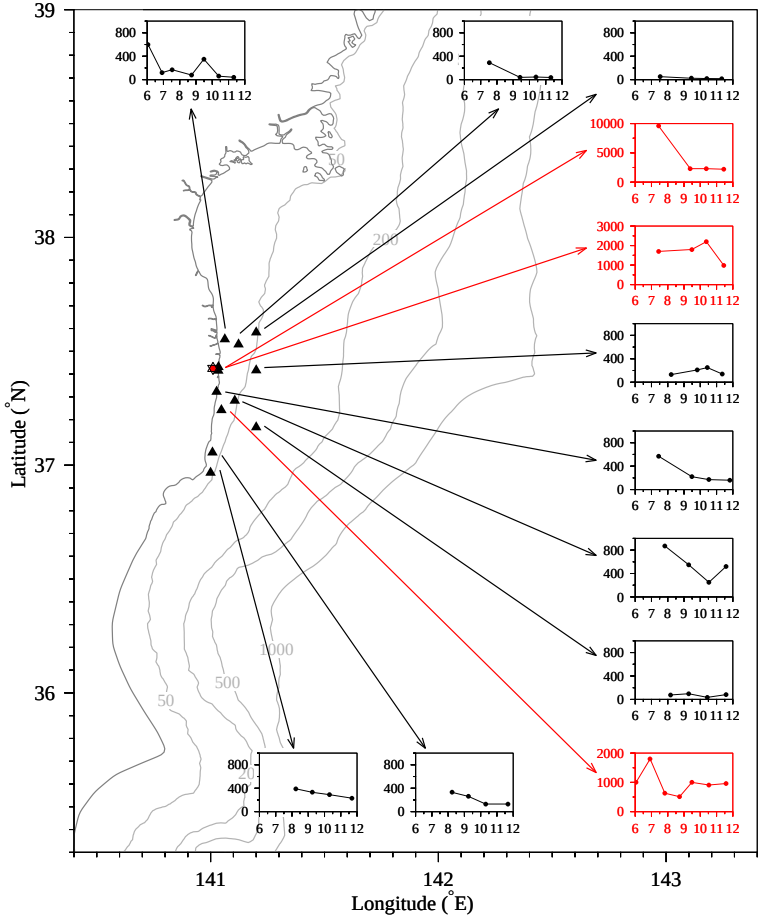

Fig. 14. Spatial and temporal distribution of ^{137}Cs concentration in sediments in the near-shore area. The data unit is Bq kg^{-1}.

BGD
10, 1929–1955, 2013