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RAPID COMMUNICATION

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

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KEYWORDS: Fukushima Daiichi nuclear power plant disaster, oceanic dispersion simulation, ^{131}I, ^{137}Cs, SEA-GEARN, ocean general circulation model, WSPEEDI-II, deposition, oceanic concentrations, released amounts

I. Introduction

It was reported that after the magnitude 9.0 earthquake and resulting tsunami that occurred on March 11, 2011, some radioactive material, including iodine and cesium, was discharged into the Pacific Ocean because of the Fukushima Daiichi nuclear power plant (NPP) disaster. High concentrations of ^{131}I and ^{137}Cs were found in the seawater and the seabed sediment along the coastline of Fukushima Prefecture. In addition, radionuclides were detected in marine products caught near Fukushima Prefecture. In response to this situation,

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assessment of the distribution of concentrations of radioactive materials by means of computer simulation as well as oceanic survey is urgently required. The Japan Atomic Energy Agency (JAEA), in cooperation with Japan Marine Science Foundation and Kyoto University, has been working on numerical experiments to predict the spread of ^{131}I and ^{137}Cs in the marine environment and to estimate how much of these materials were released. The numerical experiments were carried out using the oceanic dispersion model SEA-GEARN and the ocean general circulation model (OGCM) developed by Kyoto University and Japan Marine Science Foundation. The numerical experiments took into account depositions calculated by the atmospheric dispersion model GEARN in WSPEEDI-II of ^{131}I and ^{137}Cs released into the atmosphere. The numerical experiments were performed from March 12 to April 30, 2011. This paper focuses on the amounts of ^{131}I and ^{137}Cs that were released during the above-mentioned period, as well as the concentrations of these materials in the seawater.

II. Description of Numerical Experiments

1. Oceanic Forecasting System of Radioactive Materials

An oceanic forecasting system of radioactive materials was originally developed by Japan Marine Science Foundation, Kyoto University, and JAEA to assess the radioactive materials that could be released in the future from a spent nuclear fuel reprocessing plant in Rokkasho-mura, Aomori Prefecture[1,2]. The system is composed of the three-dimensional OGCM developed at Kyoto University and Japan Marine Science Foundation[3] and the oceanic dispersion model SEA-GEARN developed at JAEA[4].

A nesting method enables the implementation of a downscale calculation from the largest area, including the entire North Pacific with horizontal resolutions of 1/8° in latitude and 1/6° in longitude, to the nested finer domain around Japan with horizontal resolutions of 1/24° in latitude and 1/18° in longitude, corresponding to about 6 km. A similar downscale experiment can be performed using the above model around Japan to calculate an oceanic condition, such as ocean current, temperature, salinity and sea surface elevation in the coastal

area, the horizontal resolutions of which are 1/72° in latitude and 1/54° in longitude, corresponding to about 2 km. The OGCM with horizontal resolutions of 1/8° × 1/6° was driven by wind, heat flux, salt flux, *etc.*, that were obtained from the climatological data from the Ocean Model Intercomparison Project (OMIP)[5]. The OGCM with horizontal resolutions of 1/24° × 1/18° was driven by the dataset from the National Centers for Environmental Prediction–Department of Energy (NCEP-DOE) Reanalysis 2[6]. The finest OGCM with horizontal resolutions of 1/72° × 1/54° was also forced by the dataset from NCEP-DOE Reanalysis 2 except for the Mesoscale Model (MSM) wind data, which were constructed by the Japan Meteorological Agency (JMA). In the downscale calculation, a data assimilation technique—the four-dimensional variational adjoint method—was used to execute a hind-cast analysis in the northwestern part of the North Pacific[7]. The assimilated data included the satellite altimeter data from Archiving, Validation and Interpretation of Satellite Oceanographic data/Collecte, Localisation, Satellites (AVISO/CLS), the sea surface temperature from Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA), *etc.* The ocean current calculated with the coastal model and the model around Japan was used as input variables in SEA-GEARN to assess the dispersion of ^{131}I and ^{137}Cs released from the Fukushima Daiichi NPP.

2. Released Amounts of ^{131}I and ^{137}Cs

Determining the released amounts of ^{131}I and ^{137}Cs presented the most difficulty because information about the source term, *e.g.*, released radionuclides, amounts, and duration, which is essential to the numerical experiments, was not available. The only information that helped us to determine the source term of radioactive materials for the numerical experiments was the concentrations of radioactive materials in the ocean reported by Tokyo Electric Power Company (TEPCO). The source term of ^{131}I and ^{137}Cs released directly into the ocean from the Fukushima Daiichi NPP was estimated as follows using monitoring data from the web site of TEPCO regarding the area near the northern and

southern discharge channels of the Fukushima Daiichi NPP[8]:

● The release point was determined to be the middle point along the coast between the northern discharge channel and the southern discharge channel of the Fukushima Daiichi NPP.

● With regard to the release duration, it was assumed that the direct release into the ocean from the Fukushima Daiichi NPP started from March 21 and continued to April 30, 2011. No direct release into the ocean was assumed before March 21 because the monitoring data were not available during this period.

● The amounts of ^{131}I and ^{137}Cs released directly into the ocean were estimated based on their concentrations at the northern and southern discharge channels of the Fukushima Daiichi NPP, which were monitored almost twice a day. First, the daily concentrations were averaged, and then the amounts of ^{131}I and ^{137}Cs at the sea surface within a volume of 1.5 km × 1.5 km × 1 m were calculated assuming that ^{131}I and ^{137}Cs with averaged concentrations exist in the volume, because the distance between the northern and southern discharge channels is about 1.5 km. Finally, the calculated amounts were adjusted by multiplying the constant obtained from a comparison of the total released amounts of ^{131}I and ^{137}Cs during 120 hours from April 1 to April 6 with the values from the report by TEPCO, which states that the total released amounts of ^{131}I and ^{137}Cs during this period were 2.8 and 0.94 PBq (1 PBq = 10^{15} Bq), respectively. **Figure 1** shows the resulting temporal variation of the released amounts of ^{131}I and ^{137}Cs for the numerical experiments.

Fig. 1

Next, the deposition of ^{131}I and ^{137}Cs released into the atmosphere was incorporated in the numerical experiments. The deposited amounts of radioactive materials from the atmosphere were calculated using the atmospheric dispersion model GEARN by taking into account the dry and wet deposition in WSPEEDI-II developed by JAEA[9,10]. Meteorological elements such as wind and precipitation were calculated in WSPEEDI-II using the initial and boundary condition from numerical forecast data (GSM-Global) from JMA, and the NCEP Reynolds optimally interpolated weekly sea surface temperature data. The released amounts

of ^{131}I and ^{137}Cs discharged into the atmosphere were given by Chino *et al.*[11]. It can be seen from Fig. 1 that the amounts released into the atmosphere are small compared to those released into the ocean at the beginning of April, and there is no information on the amounts released into the atmosphere from April 6. It was assumed, therefore, that the radioactive materials were not released into the atmosphere from April 6. The deposition amounts were calculated using GEARN with horizontal resolutions of 6 km and 2 km. The calculated deposition amounts were given to SEA-GEARN every 6 h for the wide model with horizontal resolutions of about 6 km and 78 vertical levels, and every 3 h for the narrow model with horizontal resolutions of about 2 km and 76 vertical levels.

The following two types of numerical experiments were performed in this study to evaluate the improvement in accuracy brought about by introducing the results from WSPEEDI-II: (1) only the direct release into the ocean was taken into account for the source term, (2) the direct release into the ocean and the deposition from the atmosphere were input as the source term. The numerical experiments were carried out from March 12 to April 30 and the results of the numerical experiments are described in the next section. Note that Japanese Standard Time (JST = UTC + 9 h) is used in this paper.

III. Results

Table 1 indicates the amounts of ^{131}I and ^{137}Cs released into the ocean and the atmosphere estimated by TEPCO, the Nuclear and Industrial Safety Agency (NISA), and JAEA. The total amounts released directly into the ocean from March 21 to April 30 were estimated to be about 11 PBq for ^{131}I and 4 PBq for ^{137}Cs. The total amounts released into the atmosphere from March 12 to April 5 were about 153 PBq for ^{131}I and 13 PBq for ^{137}Cs[11]. Although these values are not completely accurate, they provide important information that can be used to assess qualitatively distribution of the concentrations of radionuclides and the radiological dose to which the public was exposed as a result of the Fukushima Daiichi NPP disaster.

Table 1

Results from the numerical experiments using the coastal model with horizontal resolutions of about 2 km were validated by comparing them with the concentrations of ^{131}I and ^{137}Cs reported by TEPCO at seven sites in the ocean near the Fukushima Daiichi NPP. The concentrations of ^{131}I and ^{137}Cs calculated in the numerical experiments were in comparatively good agreement with the reported TEPCO values. **Figures 2 and 3** indicate representatively the temporal variation of concentrations of ^{131}I and ^{137}Cs from March 12 to April 30 near the northern discharge channel of the Fukushima Daini NPP and the area 15 km offshore from the Fukushima Daini NPP. It can be clearly seen that the concentrations of radioactive materials were mainly influenced by the deposition from the atmosphere before the end of March and the direct release into the ocean afterward, because there was almost no deposition from the atmosphere from the beginning of April. According to the monitoring data, high concentrations of about 4000 Bq/L for ^{131}I and 1500 Bq/L for ^{137}Cs were detected near the northern discharge channel of the Fukushima Daini NPP. On the other hand, the maximum concentrations of radioactive materials were about 200 Bq/L for ^{131}I and 300 Bq/L for ^{137}Cs in the offshore area, suggesting that the radioactive materials tended to disperse along the coast because of the southward coastal current near Fukushima Prefecture during this period. It is remarkable that in the numerical experiments, the peaks of high ^{131}I concentrations were suddenly produced near the northern discharge channel of the Fukushima Daini NPP on March 16 and in the offshore area on March 20 (Fig. 3), which was caused by the large amounts of deposition from the atmosphere (**Fig. 4**). The large amounts of ^{131}I were mainly carried to the south on March 16 and the southeast on March 20 from the Fukushima Daiichi NPP, resulting in a phenomenon of local peaks of ^{131}I concentrations.

Fig. 2

Fig. 3

Fig. 4

High concentrations of radioactive materials were detected in marine products such as young lancefish and whitebait caught near Fukushima and Ibaraki Prefectures, and this poses a serious ecological concern. In particular, a high ^{131}I concentration of 4080 Bq/kg was detected in young lancefish caught off the coast of Kita-ibaraki City on April 3 and the corresponding radioecological concentration factor for the fish is about $10^{12)}$. This suggests

that the water with a ^{131}I concentration of about 400 Bq/L existed at the sea surface off Kita-ibaraki City at that time. The concentration of about 400 Bq/L for ^{131}I could not be demonstrated by the numerical experiments with only the direct release into the ocean, which would have resulted in the ^{131}I concentration in the corresponding area of less than 10 Bq/L (**Fig. 5**). However, the supposed concentration of about 400 Bq/L was demonstrated in the numerical experiments with both the direct release into the ocean and the deposition from the atmosphere. The numerical experiments suggest that the high concentrations of radioactive materials detected in the marine products caught near Fukushima and Ibaraki Prefectures at the beginning of April were because of the deposition of radioactive materials released into the atmosphere.

Fig. 5

Numerical experiments in the model domain around Japan with horizontal resolutions of about 6 km were carried out to assess the dispersion of radioactive materials over a wide area. **Figure 6** displays the ^{131}I concentrations at the sea surface in the numerical experiments with only the direct release into the ocean, while **Figure 7** displays the ^{131}I concentrations at the sea surface in the numerical experiments with both the direct release into the ocean and the deposition from the atmosphere. The release into the atmosphere from the Fukushima Daiichi NPP reached the maximum level on March 15. It resulted in the large amounts of deposition into the ocean along Fukushima, Ibaraki, and Miyagi Prefectures and the offshore area northeast off Miyagi Prefecture with a concentration of more than 10 Bq/L on March 17 (Fig. 7). The deposited ^{131}I was subsequently carried to the south because of the Oyashio current by the end of March. On the other hand, it is found that ^{131}I directly released into the ocean after the end of March tended to be carried to the south along Fukushima and Ibaraki Prefectures, separating from the coast in the northern part of Chiba Prefecture, and then flowing eastward along the Kuroshio current with a concentration less than 10 Bq/L by the end of April (Fig. 6).

Fig. 6

Fig. 7

In the model domain, the deposited amounts of radioactive materials into the ocean and the ground during the calculation period were estimated in the numerical experiments

with the model around Japan with horizontal resolutions of about 6 km (**Table 2**). As a result, it is suggested that 57 and 67 PBq for ^{131}I was deposited into the sea surface and the ground, respectively. As for ^{137}Cs, the amounts deposited into the sea surface and the ground were estimated to be 5 and 6 PBq, respectively. These values could be slightly underestimated, because re-entry of radioactive materials going out of the model domain was not taken into account in this study.

Table 2

IV. Discussion

Numerical experiments were carried out to assess the concentrations of ^{131}I and ^{137}Cs and to estimate the amounts of ^{131}I and ^{137}Cs released directly into the ocean because of the Fukushima Daiichi NPP disaster. The results of the numerical experiments were validated by making use of the temporal variation of concentrations in the ocean reported by TEPCO. It is suggested that the high concentrations of radioactive materials in the ocean were due to the deposition from the atmosphere by the end of March and the direct release into the ocean afterward. In addition, it is also suggested by the results of the numerical experiments that the high concentrations of radioactive materials detected in marine products caught near Fukushima and Ibaraki Prefectures at the beginning of April were due to the large amounts of deposition of radioactive materials released into the atmosphere. The effect of the deposition of radioactive materials from the atmosphere was spread over a wide area of the Pacific Ocean east of Japan. It was estimated that out of the total amounts of ^{131}I and ^{137}Cs released into the atmosphere from the Fukushima Daiichi NPP, about 81% of ^{131}I and 85% of ^{137}Cs were deposited into the sea surface or the ground in the model domain (Table 2).

The numerical experiments in this study are a preliminary assessment. It will probably be necessary to estimate the source term on oceanic and atmospheric releases more accurately at some point in the future. Nevertheless, it is suggested by this study that the numerical experiments have the potential to predict the spread of radioactive materials with some accuracy. It is important for the protection and preservation of the marine environment to

assess the concentrations of radioactive materials in the seabed sediment.

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Figure captions

Fig. 1. Estimated amounts of ^{131}I and ^{137}Cs released into the ocean and the atmosphere from March to April 2011, from the Fukushima Daiichi NPP.

Fig. 2. Temporal variation of the concentrations of ^{131}I and ^{137}Cs near the northern discharge channel of the Fukushima Daini NPP (2F) and the area 15 km offshore from 2F. Gray closed circles indicate the monitoring data reported by TEPCO; black lines denote the results of the numerical experiments with only the direct release into the ocean. The monitoring sites are shown in Fig. 4.

Fig. 3. Same as Fig. 2 except that black lines denote the results of the numerical experiments with the direct release into the ocean and the deposition from the atmosphere.

Fig. 4. Deposited amounts of ^{131}I from the atmosphere into the ocean and the ground accumulated during 11 and 14 JST on March 16, 2011 and during 5 and 8 JST on March 20, 2011. Black closed squares indicate the monitoring sites shown in Figs. 2 and 3.

Fig. 5. Concentrations of ^{131}I at the sea surface at 11 JST on April 3. The left panel depicts the results of the numerical experiments with only the direct release into the ocean; the right panel depicts the results of the numerical experiments with the direct release into the ocean and the deposition from the atmosphere. White open squares indicate the Fukushima Daiichi NPP (1F). Open circles indicate the offshore area where the young lancefish with the high ^{131}I concentration were caught on April 3, 2011.

Fig. 6. Concentrations of ^{131}I at the sea surface from March to April 2011. Results shown are from the numerical experiments with only the direct release into the ocean.

Fig. 7. Same as Fig. 6 except that results shown are from the numerical experiments with the direct release into the ocean and the deposition from the atmosphere.

Table 1 Amounts of ^{131}I and ^{137}Cs released into the ocean and the atmosphere estimated by TEPCO, NISA, and JAEA (PBq).

		^{131}I	^{137}Cs
Ocean	TEPCO (4/1 – 4/6)	3	1
	JAEA (3/21 – 4/30)	11	4
Atmosphere	NISA	160	15
	JAEA (3/12 – 4/5)	153	13

Table 2 Amounts of ^{131}I and ^{137}Cs deposited into the ocean and the ground in the model domain from March 12 to April 30, 2011 as determined by the numerical experiments (units of PBq). Numbers in parentheses represent the ratio of total deposited amounts to total released amounts into the atmosphere of 153 PBq for ^{131}I and 13 PBq for ^{137}Cs.

	^{131}I	^{137}Cs
Total	124 (81%)	11 (85%)
Ocean	57	5
Ground	67	6

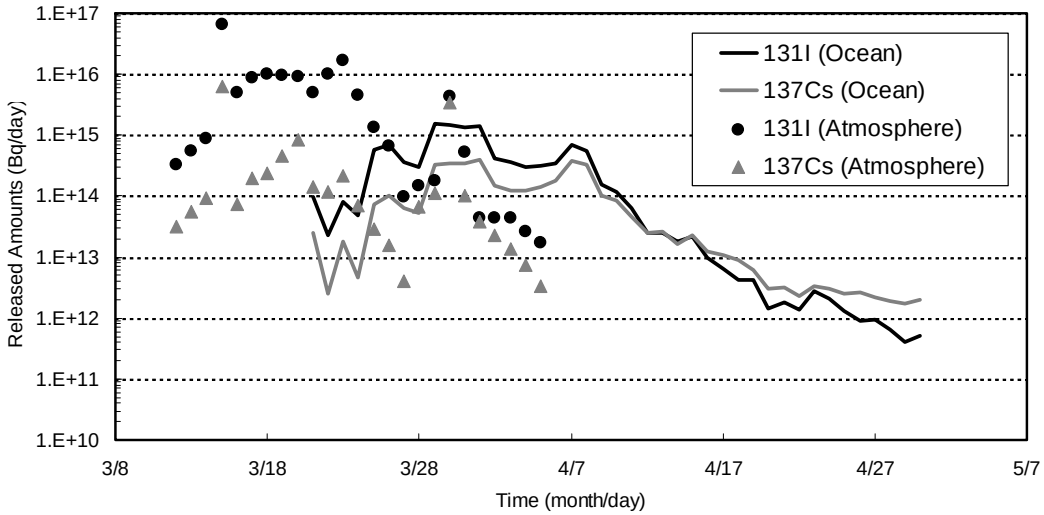

Fig. 1

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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

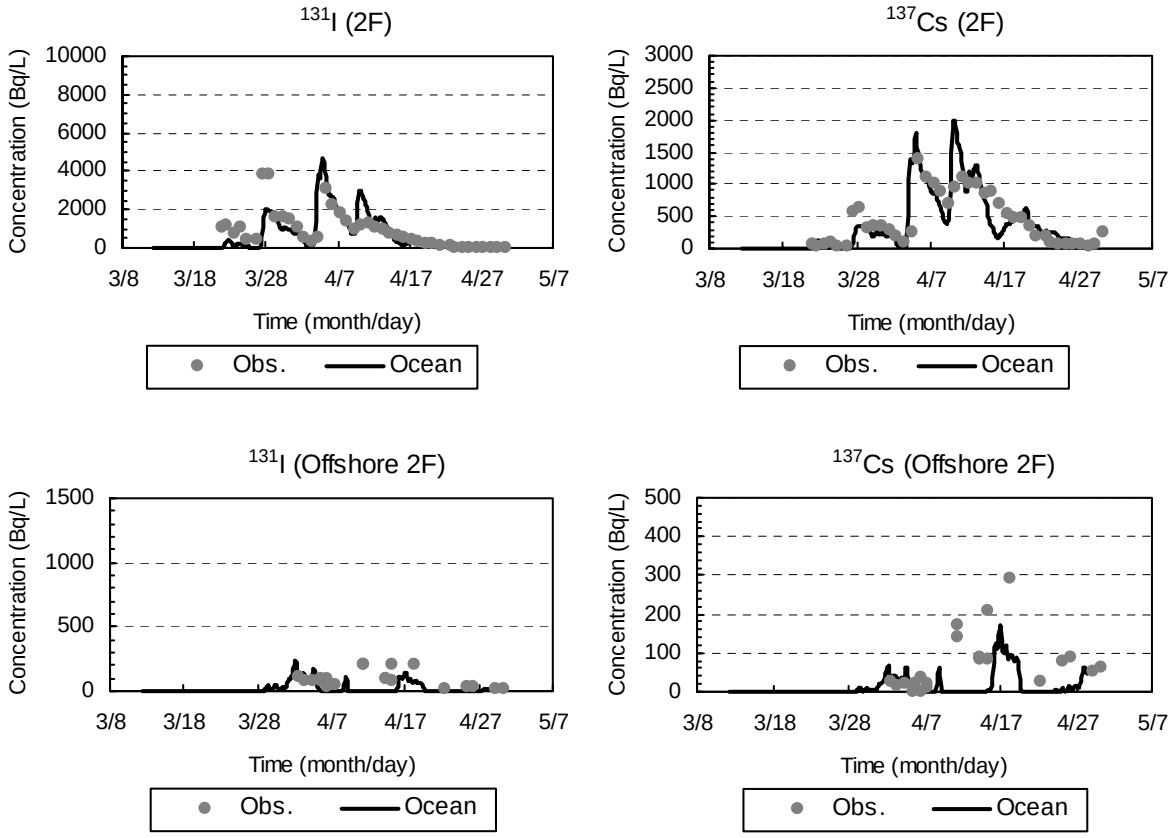

Fig. 2

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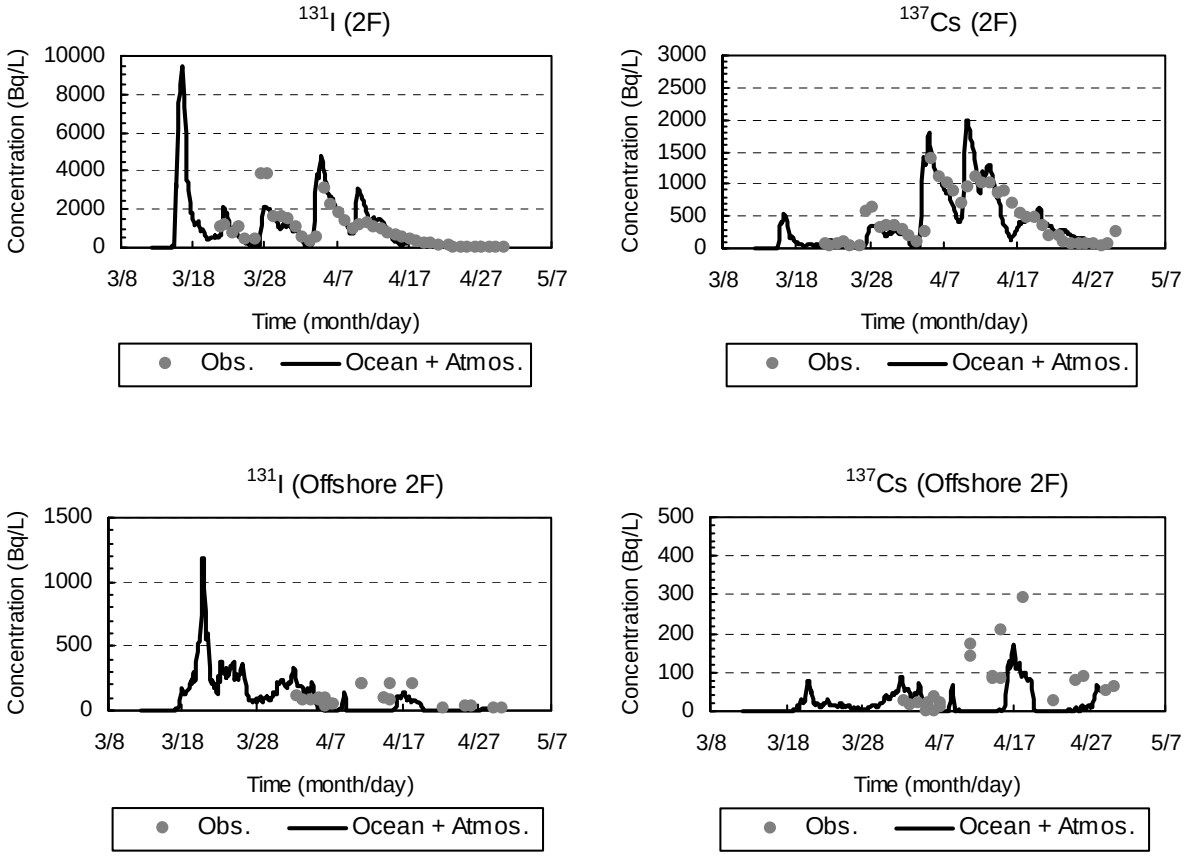

Fig. 3

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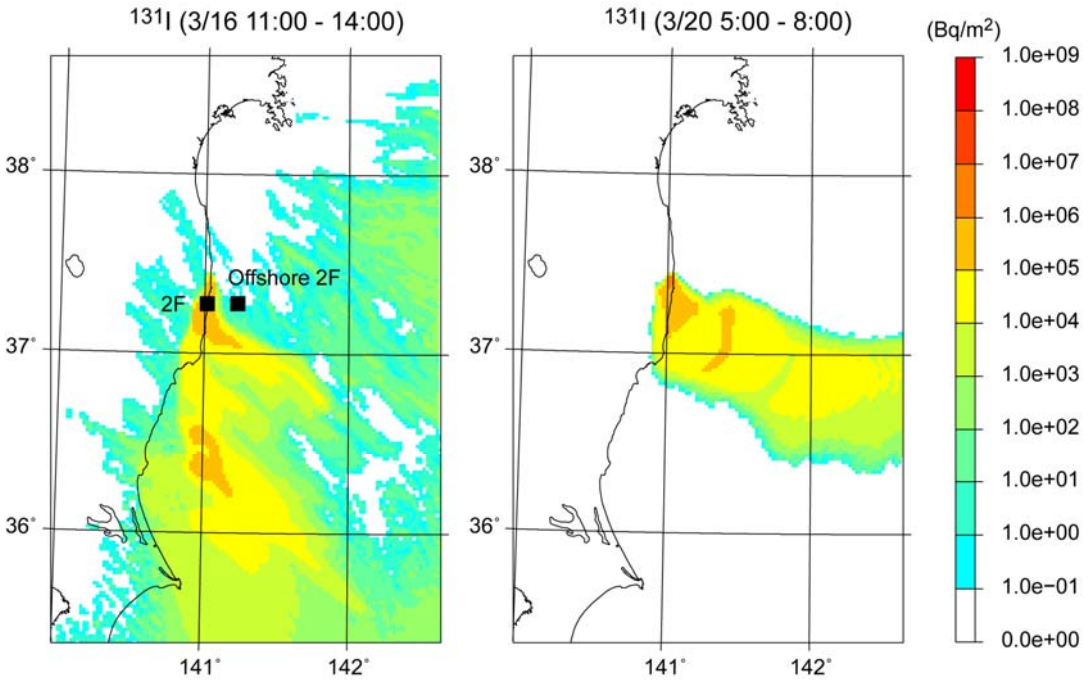

Fig. 4

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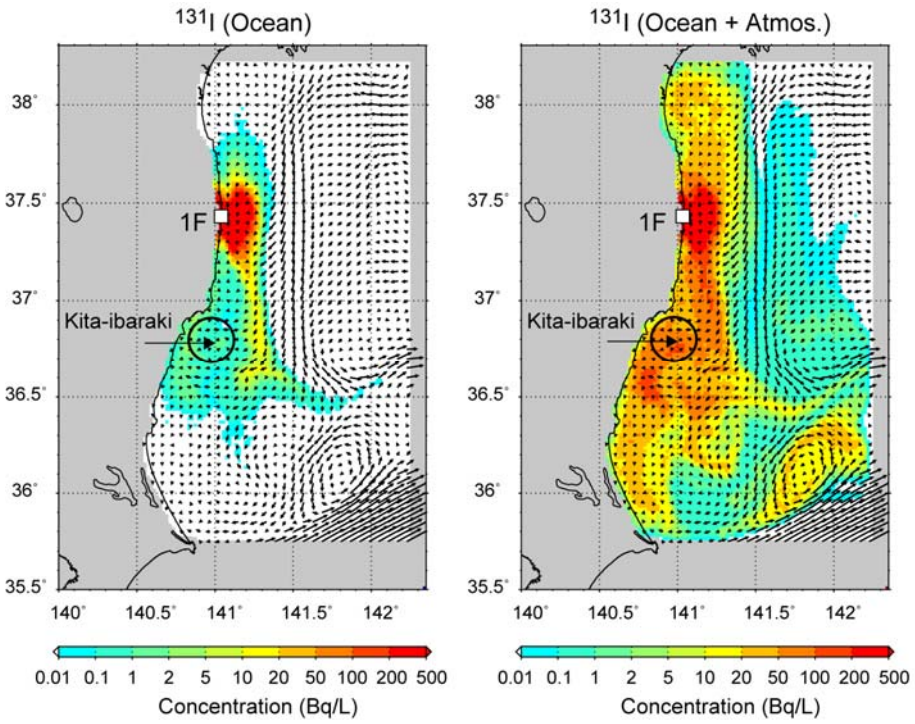

Fig. 5

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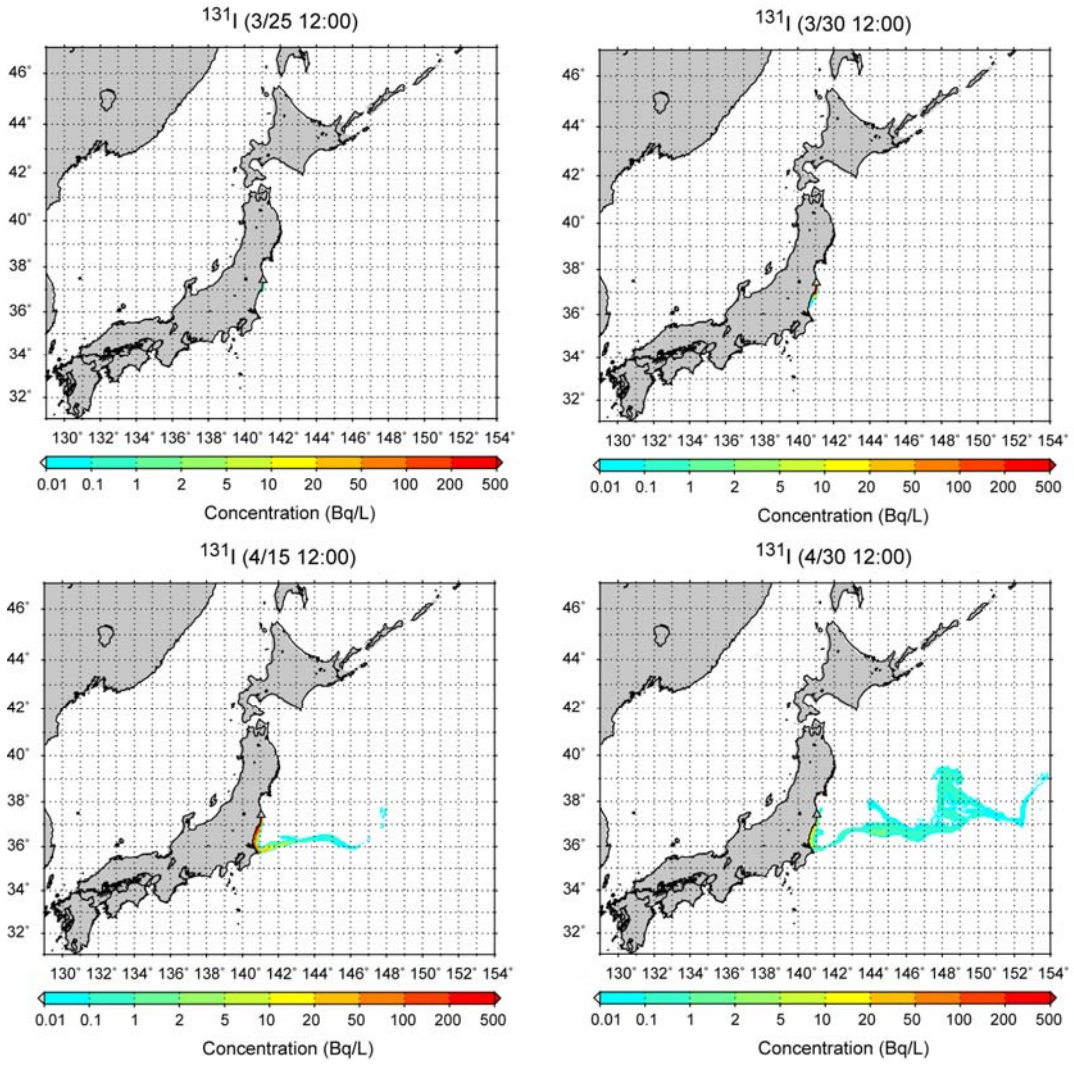

Fig. 6

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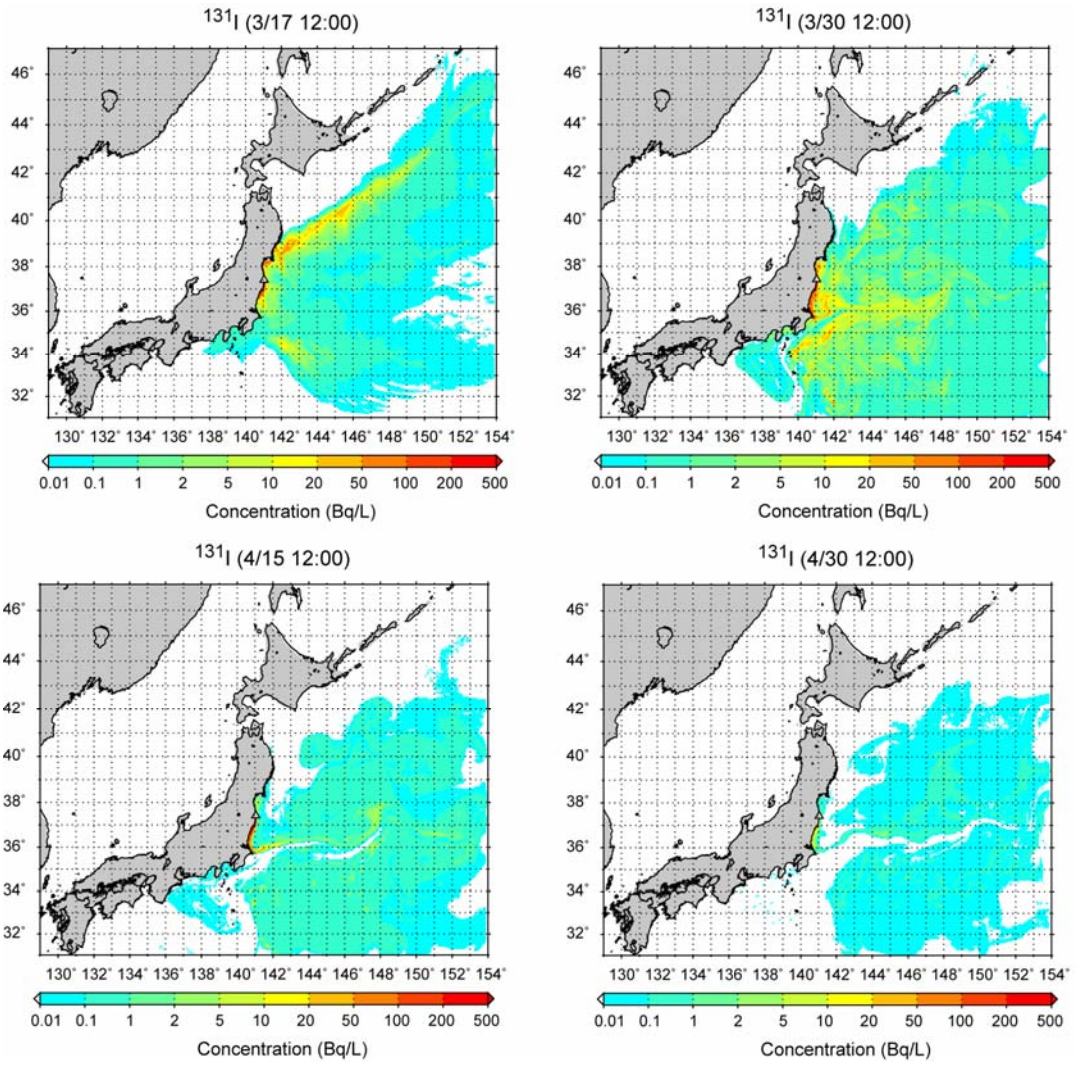

Fig. 7

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