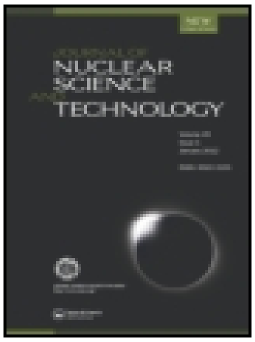

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TECHNICAL MATERIAL

Development of a short-term emergency assessment system of the marine environmental radioactivity around Japan*

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ABSTRACT
The Japan Atomic Energy Agency (JAEA) has, for many years, been developing a radionuclide dispersion model for the ocean, and has validated the model through application in many sea areas using oceanic flow fields calculated by the oceanic circulation model. The Fukushima Dai-ichi Nuclear Power Station accident caused marine pollution by artificial radioactive materials to the North Pacific, especially to coastal waters northeast of mainland Japan. In order to investigate the migration of radionuclides in the ocean caused by this severe accident, studies using marine dispersion simulations have been carried out by JAEA. Based on these as well as the previous studies, JAEA has developed the Short-Term Emergency Assessment system of Marine Environmental Radioactivity (STEAMER) to immediately predict the radionuclide concentration around Japan in case of a nuclear accident. Coupling the STEAMER with the emergency atmospheric dispersion prediction system, such as Worldwide version of System for Prediction of Environmental Emergency Dose Information version II (WSPEEDI-II), enables comprehensive environmental pollution prediction both in air and the ocean.

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Radionuclide dispersion model; ocean; SEA-GEARN; STEAMER; WSPEEDI-II; emergency assessment model system; severe accident

1. Introduction

Mathematical marine dispersion models of radionuclide migration have been developed to assess the impact of routine and accidental releases of radioactive materials through various nuclear activities such as weapons production and testing, power plants, fuel reprocessing plants, and waste disposal [1]. Released radionuclides migrate in the ocean by physical, chemical, and biological processes such as advection, diffusion, adsorption, desorption, bioaccumulation, sedimentation, re-suspension, bioturbation, and diagenesis. The migration processes of radionuclide in ocean are solved using an oceanic circulation model and a dispersion model. Radionuclide distribution in the ocean significantly depends on the oceanic flow fields (e.g. [2]). Recent numerical oceanic circulation modeling results were consistent with observations, in terms of not only the distribution pattern of a model variables but their physical quantity. This progress in numerical modeling has been accompanied by the development of synthetic systems for modeling and observation, i.e. data assimilation techniques. Data assimilation is a series of combined treatment of numerical results and observation that provide a regular output in space and time [3]. The oceanic circulation model with the data assimilation techniques was used to obtain optimum initial oceanic fields (now-cast) for numerical forecasting.

The Japan Atomic Energy Agency (JAEA) has, for many years, been developing a radionuclide dispersion model for the ocean, and has validated the model through application in many sea areas using oceanic flow fields calculated by the oceanic circulation model with the data assimilation techniques. For example, Kobayashi et al. [4] developed the radionuclide migration forecasting system to predict the routine and accidental releases of liquid radioactive wastes during the operations of a spent nuclear fuel reprocessing plant in Aomori Prefecture, Japan. This system consists of an ocean general circulation model coupled with a data assimilation system with the four-dimensional (4D) variational adjoint method to execute the hind-cast analysis developed by Kyoto University [5,6] and a particle random-walk radionuclide dispersion model for the ocean developed by JAEA [7]. The experimental results of hind-casting for the coastal area and the hypothetical release of radionuclides indicated that the migration of radionuclides depends on the current direction at the release point, just after the release.

Considerable radionuclides were discharged into the environment due to the Fukushima Dai-ichi Nuclear Power Station (FNPS1) accident in Japan in March 2011. Radionuclides released from FNPS1 were transported through the atmosphere and the ocean. Moreover, water used to cool a damaged nuclear reactor leaked into the ocean. These radioactive materials caused a severe marine pollution [8].

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*This paper presents the details of STEAMER, oceanic dispersion flow fields used as input oceanographic data, the radionuclide dispersion model in the ocean, and performance test results.

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Regarding the FNPS1 accident, various environmental assessments have been performed by many research groups including JAEA using marine dispersion simulations. Consequently, it was recognized that the risk of radionuclide release from nuclear facilities to the environment was very high and the establishment of emergency ocean dispersion forecasting systems was necessary. For example, the French Institute for Radiological Protection and Nuclear Safety (IRSN) developed emergency response tools for accidental radiological contamination of French coastal areas [9]. JCOMM, the Joint WMO-IOC (World Meteorological Organization–UNESCO's Intergovernmental Oceanographic Commission) Technical Commission for Oceanography and Marine Meteorology, developed a response strategy for marine environmental emergencies such as the FNPS1 accident, in consultation with partners including International Maritime Organization and International Atomic Energy Agency (IAEA), as well as its members/member states [10].

In this study, we have developed the Short-Term Emergency Assessment system of Marine Environmental Radioactivity (STEAMER) to immediately predict the radionuclide migration for a nuclear accident in ocean around Japan, by integrating previous study results. Until now, post-analysis of oceanic radionuclide dispersion prediction was mainly carried out because long CPU time was necessary to calculate oceanic flow fields. At such time, the Japan Meteorological Agency (JMA) has started to provide the online forecast data of oceanic flow fields to the public through Japan Meteorological Business Support Center (JMBSC). By using online forecast data, the immediate prediction of oceanic radionuclide dispersion is available. These emergency prediction results can aid decision-makers in preventing radiation exposure. STEAMER has functions of automatic prediction with a fixed calculation condition, manual prediction with any calculation conditions. It can also input the atmospheric deposition data from the emergency atmospheric dispersion prediction system, Worldwide version of System for Prediction of Environmental Emergency Dose Information version II (WSPEEDI-II) developed by JAEA [11]. STEAMER started its test operation using the automatic prediction function in September 2014. As a test operation, hypothetical Cs-137 release calculations for two nuclear facilities in Japan are carrying out every day to validate the stability of a system.

In Section 2, we describe the oceanic flow fields, as well as the ocean dispersion model and its validation results. In Section 3, we explain the performance test of the system. In Section 4, conceivable utilizations and limitations of STEAMER are discussed.

2. Overview of the model system

STEAMER executes the oceanic dispersion simulation by a particle random-walk model, SEA-GEARN developed by JAEA [7] with pre-computed oceanic flow fields. By using online forecast data of oceanic flow fields, the immediate prediction of oceanic radionuclide dispersion is available. Details of the oceanic flow field data and ocean dispersion model are described in this section.

2.1. Oceanic flow fields

Radionuclide distribution in the ocean significantly depends on the oceanic flow fields (e.g. [2]). Even if predicted performance in the oceanic flow fields improves, uncertainty of the predicted oceanic flow fields by an oceanic circulation model remains as a problem which should be considered. In other words, the ensemble mean fields by several oceanic circulation models provide reasonable result [12]. However, this technique, which requires long computing time, is not realistic in emergency ocean dispersion forecasting systems. Therefore, STEAMER executes oceanic dispersion simulations with pre-computed variable of three-dimensional (3D) oceanic flow fields by Meteorological Research Institute (MRI) Multivariate Ocean Variational Estimation (MOVE; [13]) and the Global operational Real-Time Ocean Forecast System (Global RTOFS; [14]) by the National Oceanic and Atmospheric Administration (NOAA) to predict the distribution of radionuclides. Due to the difference of prediction periods as shown in following sections, we adopted to use the oceanic flow fields by MOVE and Global RTOFS as an emergency prediction for 30 days and 8 days, respectively. By employing these flow fields, STEAMER is used to forecast the radionuclide distribution in the western North Pacific and the North Pacific.

2.1.1. MOVE

MOVE was developed at MRI/JMA, and was used for numerical reanalysis/forecast products for the western North Pacific (MOVE-WNP) and the North Pacific (MOVE-NP). The MOVE-WNP model domain extends from 15° N to 65° N meridionally and from 117° E to 160° W zonally. The horizontal resolution is 1/10° (from 15° N to 50° N) and 1/6° (from 50° N to 65° N) meridionally, and 1/10° (from 117° E to 160° E) and 1/6° (from 160° E to 160° W) zonally. MOVE-NP spans from 15° S to 65° N meridionally and from 100° E to 75° W zonally, with a horizontal resolution of 1/2°. MOVE-WNP and MOVE-NP have the same vertical grid spacing with 54 levels. The outputs of MOVE-WNP and MOVE-NP have been provided to the public from the JMBSC since 7 August 2014. The MOVE now-cast and 30-days prediction products are provided as daily averaged oceanographic data including sea surface height, temperature, salinity, and horizontal current velocities. MOVE is based on the MRI Community Ocean Model (MRI.COM; [15]) assimilated with a huge amount of satellite and *in situ* data, including Advanced Research and Global Observation

(ARGO) floats using the 3D variational method. Therefore, MOVE can reproduce the oceanic hydrodynamics accurately, especially in the western North Pacific. For example, the simulated variations in the Kuroshio transports crossing the Affiliated Surveys of the Kuroshio off Cape Ashizuri line and the Pollution Nagasaki line showed a quite close agreement with observations [13].

2.1.2. Global RTOFS

Global RTOFS is an operational ocean forecast system at the Environmental Modeling Center (EMC)/NOAA. It is based on an eddy resolving 1/12° global HYbrid Coordinate Ocean Model (HYCOM; [16]) with 32 vertically stretched hybrid layers. Global RTOFS provides eight-day oceanic forecast data assimilated with various *in situ* and satellite observations using the Navy Coupled Ocean Data Assimilation [17]. Global RTOFS results are provided from the web page of EMC/NOAA as daily and three-hourly averaged oceanographic data. The results of the global model were shown to agree well with satellite altimetry data [14]. Especially, the Gulf Stream location in the model was compared to the location estimated by satellite advanced very-high-resolution radiometer sea surface temperature (AVHRR SST), ship, and buoy data to demonstrate that the Gulf Stream path was successfully reproduced.

2.2. Ocean dispersion model

2.2.1. Description of ocean dispersion model

A particle random-walk model, SEA-GEARN, is used as a radionuclide dispersion model in the ocean [7]. The dispersion of released radionuclide in the ocean is modeled by the trajectories of many virtual particles to numerically solve the advection–diffusion equation. SEA-GEARN uses 3D velocity data as input variables. In general, radionuclides exist in three phases in the ocean: dissolved in seawater, adsorbed on large particulate matter, which assumes an aggregate with a single radius and density with settling velocity, and adsorbed on active bottom sediment. Two types of radionuclide releases are considered: release into the ocean directly from the facility and atmospheric deposition to the sea surface. SEA-GEARN calculates the dissolved radionuclide concentration in the sea (Bq m^{-3}), the particulate radionuclide concentration in the sea (Bq m^{-3}), and the sediment radionuclide concentration at the seabed (Bq m^{-2}). The concentration at each unit Eulerian cell is calculated by summing up the contribution of each virtual particle to the cell.

2.2.2. Validation of ocean dispersion model

SEA-GEARN was validated in the application to hindcast the migration of the radionuclides released due to the FNPS1 accident [18]. The model structure of this system is quite similar to that of STEAMER, except for the input variables of the oceanic flow fields. In order to simulate the oceanic dispersion, the source term of the direct release to the ocean was estimated using ocean monitoring data and the atmospheric deposition [19] calculated by WSPEEDI-II. The temporal variations in the concentrations of I-131 and Cs-137 from March 12 to the end of April, near the northern discharge channel of the Fukushima Dai-ni Nuclear Power Station (FNPS2) and in the area 15 km offshore from the FNPS2, agreed well with the measurements. The concentrations of radioactive materials were found to be mainly influenced by the deposition from the atmosphere before the end of March and the direct release into the ocean afterward.

3. Performance test of STEAMER

Performance test of STEAMER has been carried out to validate the accuracy of prediction results and the stability and robustness of the system. Details of the computer specification, processing flow, validation of the system, and automatic prediction function of oceanic radionuclide dispersion are described in this section.

3.1. Overview

In the performance test, STEAMER has been operated on the computational environment that consists of one data reception server, which receives oceanographic data from JMBSC/JMA, and two simulation/visualization servers (primary and secondary servers), which receive oceanographic data from EMC/NOAA and predict radionuclide dispersion in the ocean based on SEA-GEARN conducted with parallelization by Message Passing Interface. The data reception server is a Linux-based computer equipped with QEMU Virtual CPU version (cpu64-rhel6), with memory size of 8 GB. Intel(R) Xeon(R) CPU E5-2697 v2 is used as the simulation/visualization server, with memory size of 198 GB. The secondary server is synchronized with the primary server to raise fault-tolerance.

Figure 1 shows the processing flow of STEAMER. The received oceanographic data from JMBSC/JMA are sent to the simulation/visualization servers and are edited for calculation by SEA-GEARN, as shown in Table 1. The horizontal and vertical resolutions are the same as in the original oceanographic data. The vertical velocity is not included in the received oceanographic data because it is not a prognostic but a diagnostic variable in both MOVE and Global RTOFS. Therefore, the vertical velocity is obtained by vertically integrating the continuity equation from top to bottom [15].

The oceanic dispersion forecast is conducted with oceanic forecast data by MOVE (Global RTOFS) for 30 (8) days corresponding to the oceanic forecast periods. The output variable of the models is currently only the dissolved phase radionuclide concentration to save

Table 1. Calculation conditions of oceanic dispersion simulation in STEAMER.

	MOVE-WNP	MOVE-NP	Global-RTOFS
Objective area	117° E–160° E, 15° N–50° N	100° E–75° W, 0° N–65° N	117°E–160°E, 15°N–50°N
Horizontal resolution	0.1°	0.5°	0.08°
Prediction period	30 days	30 days	8 days
Release settings	Point source at any locationTime variation of release rate		
Output	Dissolved radionuclide concentration		

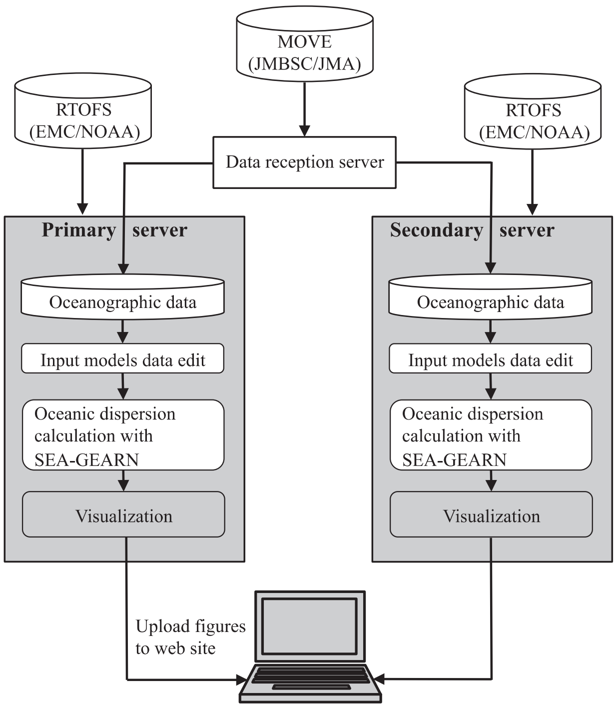

Figure 1. Processing flow of STEAMER.

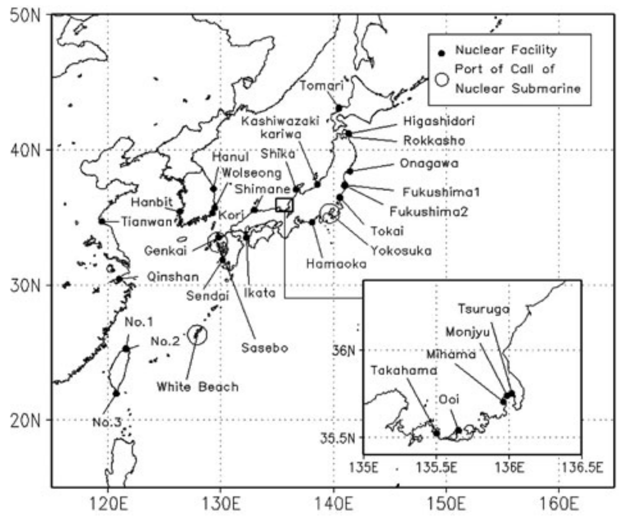

Figure 2. Sites of nuclear power plants, nuclear fuel reprocessing plant, and military harbor.

the calculation time, although SEA-GEARN can provide the three-phase interaction of radionuclides. The predicted radionuclide migration is visualized using the visualization software GrADS (Grid Analysis and Display System).

Figure 2 shows the locations of the nuclear power plants, the nuclear fuel reprocessing plant, and the military harbor with nuclear-powered ships anchored at the port. This positioning information is already installed in STEAMER.

3.2. Validation of the system

The FNPS1 accident was used as a validation scenario, focused on radioactive cesium concentration in the coastal area northeast of mainland Japan. The methodology was basically the same as that of STEAMER, except that the offline data of oceanic flow fields of MOVE and Global RTOFS were used. Actually, STEAMER has no oceanic flow fields data in 2011 because performance test has begun from September 2014. Therefore, we got oceanic flow fields data by MOVE from MRI and downloaded the data by HYCOM (https://hycom.org/), which is an original oceanic circulation model of Global RTOFS. Essentially, the respective oceanic flow fields are same as the data received in STEAMER. In order to simulate the oceanic dispersion, the source term of the direct release to the ocean [18] with the atmospheric deposition of the latest atmospheric release amount estimated by Katata et al. [20] was used.

Model results showed that airborne Cs-137 mainly spread northeastward in April 2011, whereas Cs-137 was released directly from FNPS1 into the ocean and transported eastward by the Kuroshio Extension (Figure 3). Figure 4 shows a comparison between the simulated and observed surface Cs-137 concentrations in the area 15 km offshore Uketogawa and FNPS2. The surface Cs-137 concentration in the coastal area of Fukushima Prefecture attained its maximum value in early April 2011 and decreased exponentially afterward until May 2011. The simulated Cs-137 concentration in the coastal area using oceanic flow fields by MOVE reproduced a large part of the observed Cs-137 concentration within a factor of 10, one month after the FNPS1 accident. The simulated results using oceanic flow fields by HYCOM estimated the observed Cs-137 concentration qualitatively, but a large part of the period showed underestimate tendency. If we assume that MOVE has reproduced the actual oceanic flow fields, HYCOM would forecast a strong flow field compared with MOVE. Therefore, we adopted to use a result by MOVE as a principal and employ a result by Global

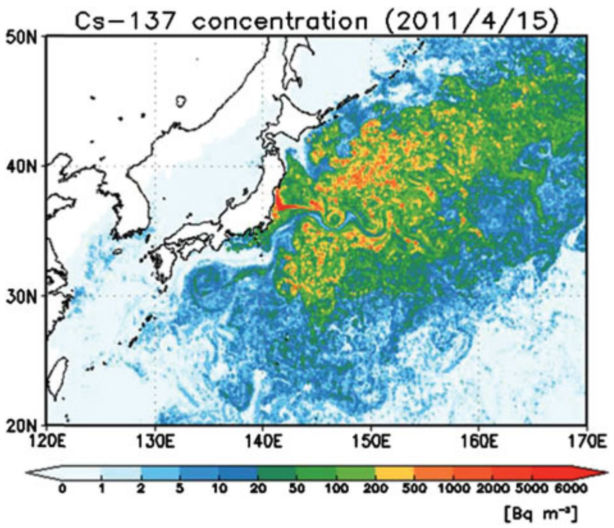

Figure 3. Simulated surface Cs-137 concentration in the western North Pacific using oceanic flow fields by MOVE on 15 April 2011.

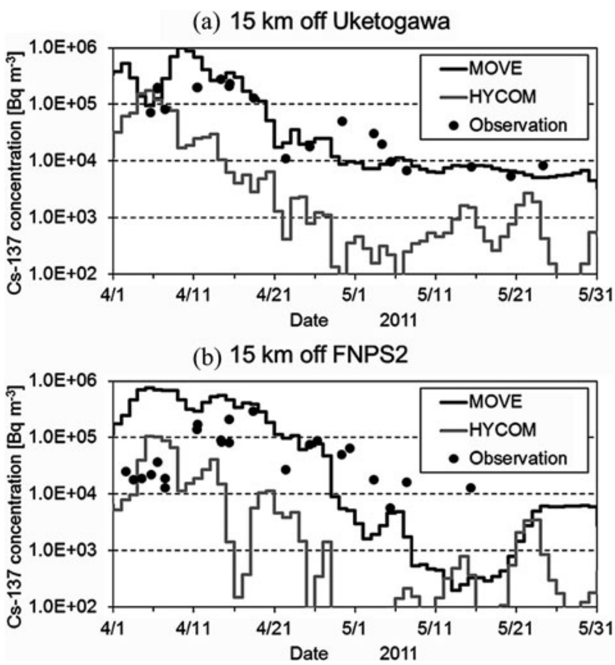

Figure 4. Temporal variations in simulated and observed surface Cs-137 concentrations in the area 15 km offshore Uketogawa and FNPS2 in April and May 2011.

RTOFS as comparison to predict the radionuclide concentration around Japan.

As mentioned earlier, SEA-GEARN and oceanographic data calculated by MOVE and Global RTOFS (HYCOM) enabled us to perform oceanic dispersion simulations to settle the marine pollution problems. Thus, STEAMER provides useful information on oceanic dispersion of radionuclides released from nuclear facilities during an emergency.

3.3. Automatic prediction function of oceanic radionuclide dispersion

The stability and robustness of the system has been validating by automatic prediction function since

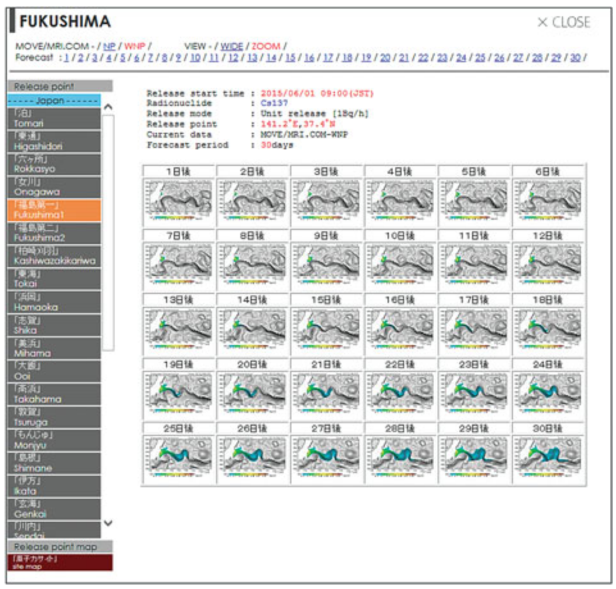

Figure 5. Example from the JAEA internal server; predicted sea surface Cs-137 concentration hypothetically released from FNPS1 on 31 May 2015.

September 2014. STEAMER is carrying out hypothetical Cs-137 release calculations for the Sendai nuclear power plant, which is in operation, and for FNPS1, which suffers from radionuclide leakage risk during its decommissioning. Radionuclides are directly released into the ocean from a point source and the unit release (1 Bq h^{-1}) continues from the beginning to the end of the calculation in the model (continuous release mode). This calculation is conducted by MOVE-WNP, MOVE-NP, and Global RTOFS. As for the calculations by MOVE-WNP, another type of release is considered, namely the unit release that continues 24 h from the beginning of the calculation (one-shot release mode).

The following operations are automatically conducted every day: data reception, converting received oceanographic data to input data for SEA-GEARN, unit release calculation of two types of release modes and three types of input oceanographic data at the two nuclear power plant sites by SEA-GEARN, visualizing and uploading resultant figures to the JAEA internal server. Figure 5 shows an example from the JAEA internal server with the predicted sea surface Cs-137 concentration hypothetically released from FNPS1 on 31 May 2015.

Table 2 shows typical computation times of SEA-GEARN and obtained input data for SEA-GEARN. The main parameters affecting the computation times are the file sizes of the received data-set, the time step, and the number of particles in SEA-GEARN.

During the period from September 2014 to September 2016, the system has not stopped other than the rolling blackouts of the research institute. The experimental results on automatic prediction function demonstrated the stability and robustness of the system.

Table 2. Typical computation times and obtained input data for SEA-GEARN.

Operation	Input models	CPU used	CPU time
SEA-GEARN 30 days prediction (30 days continuous release) Grid size: 372 × 132 × 54	MOVE-NP	3	180 min
SEA-GEARN 30 days prediction (30 days continuous release) Grid size: 430 × 350 × 54	MOVE-WNP	3	180 min
SEA-GEARN 8 days prediction (8 days continuous release) Grid size: 541 × 441 × 32	Global RTOFS	8	15 min
Obtained input data for SEA-GEARN (including reception from the organizations and data conversion)	MOVE-NP	1	15 min
	MOVE-WNP	1	45 min
	Global RTOFS	1	435 min

4. Discussion

4.1. Conceivable utilizations of STEAMER

When the source term from a facility is obtained due to an accident, it is necessary to change the source term. Furthermore, when an accident occurs at a nuclear ship/submarine that is being sailed, it is necessary to set the release position and depth. Accordingly, the following configurations of STEAMER are changeable: types of radionuclides, types of release mode (direct release from the ocean, atmospheric deposition calculated by WSPEEDI-II, and direct release from the ocean with atmospheric deposition), time variability in release rate, release position and depth, time step, and output time interval. Namely, the parameters of this system can be changed, and the system can conduct calculation using preserved oceanographic data by manual control. Therefore, it is also possible to use STEAMER to design oceanic nuclear pre-accident countermeasures and to use oceanic nuclear post-accident assessment.

The prediction of pollution in a sea area allows the establishment of the following measures:

- Setting up an emergency ocean monitoring sea area corresponding to a realistic pollution area.
- Prohibiting fishing and sailing sea area, since these activities contribute to internal exposure through ingestion of marine products and desalinated water.
- Estimating the source term of oceanic release from a facility through the ocean dispersion model and ocean monitoring data.
- Estimating the source term of atmospheric release from a facility through the atmosphere and ocean dispersion model and the land/ocean monitoring data.

Among these, the first two items can aid decision-makers in preventing radiation exposure, whereas the last two items can be used by researchers to assess the environmental impact.

Information on the source term to the ocean is very important in case of an accident, but it cannot be easily obtained. To solve this problem, reverse estimation of the source term is performed by measuring the radionuclides' ocean concentration. We explain the estimation method as follows.

The reverse estimation method is used to calculate the release rates of radionuclides (Bq h^{-1}) by coupling ocean monitoring data with ocean dispersion simulations, assuming unit release rate (1 Bq h^{-1}). Release rates are obtained by dividing the observed ocean concentration of radionuclides with the calculated concentrations at the sampling points, as follows:

$$Q_i = M_i / C_i, \quad (1)$$

where Q_i is the release rate (Bq h^{-1}) of radionuclide i when discharged into the ocean, M_i is the observed concentration (Bq m^{-3}) of radionuclide i, and C_i is the dilution factor (h m^{-3}) of radionuclide i, which is equal to the ocean concentration calculated if the release rate is equal to 1 [19].

However, this method may not be applied when the release rates vary in time or with instantaneous release. In these cases, a multiple times simulation with a unit release of short duration must be executed, followed by the integration or calculation of multiple calculation results, as appropriate [21].

If the atmospheric deposition is considered with direct release to the ocean, an atmosphere and ocean dispersion simulation is carried out. When the release rates vary in time or under instantaneous release of the atmospheric source term, measurements of the air/ocean concentration of radionuclides or its dose rate in the environment are used [20,21].

4.2. Limitations of STEAMER

Two main issues arose during the performance test. One is the long calculation time, as shown in Table 2. This result derived from the performance test of STEAMER. This issue will be solved by introducing large-scale calculation servers in the actual operation of STEAMER. The other issue is the coarse horizontal resolution of the system. It is difficult to resolve the complicated coastal current with the 0.1° (0.08°) horizontal resolution of the oceanographic data by MOVE-WNP (Global RTOFS). The 1 km horizontal resolution model has been validated to solve this issue [22], and the results will be published in a subsequent paper.

5. Conclusion

JAEA has developed a tool to be used in the event of a radionuclide accident in the ocean around Japan.

The initial forecasting results of STEAMER coupling with WSPEEDI-II for an accident will offer useful information to decision-makers and scientists, such as the sea area requiring emergency monitoring and prohibition of fishing and sailing, to prevent radiation exposure and source term estimation. STEAMER is also used for designing oceanic nuclear pre-accident countermeasures and for the oceanic nuclear post-accident assessment using the preserved oceanographic data.

From the validation results of performance test and stability/robustness test of automatic prediction function since September 2014, it can be concluded that STEAMER is sufficient for operating emergency prediction of the radionuclide concentration in ocean around Japan in case of a nuclear accident.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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