Journal of Environmental Radioactivity 136 (2014) 64–75

Contents lists available at ScienceDirect

Journal of Environmental Radioactivity

journal homepage: www.elsevier.com/locate/jenvrad

Numerical simulation on the long-term variation of radioactive cesium concentration in the North Pacific due to the Fukushima disaster

Hideyuki Kawamura [a, *], Takuya Kobayashi [a], Akiko Furuno [a], Norihisa Usui [b], Masafumi Kamachi [b]

[a] Sector of Nuclear Science Research, Japan Atomic Energy Agency, Japan
[b] Meteorological Research Institute, Japan Meteorological Agency, Japan

ARTICLE INFO

Article history:
Received 6 September 2013
Received in revised form
28 April 2014
Accepted 7 May 2014
Available online

Keywords:
Oceanic dispersion
^{134}Cs
^{137}Cs
Fukushima Daiichi nuclear power plant
Long-term variation
Data assimilation

ABSTRACT

Numerical simulations on oceanic ^{134}Cs and ^{137}Cs dispersions were intensively conducted in order to assess an effect of the radioactive cesium on the North Pacific environment with a focus on the long-term variation of the radioactive cesium concentration after the Fukushima disaster that occurred in March 2011. The amounts of ^{134}Cs and ^{137}Cs released into the ocean were estimated using oceanic monitoring data, whereas the atmospheric deposition was calculated through atmospheric dispersion simulations. The highly accurate ocean current reanalyzed through a three-dimensional variational data assimilation enabled us to clarify the time series of the ^{134}Cs and ^{137}Cs concentrations in the North Pacific. It was suggested that the main radioactive cesium cloud due to the direct oceanic release reached the central part of the North Pacific, crossing 170°W one year after the Fukushima disaster. The radioactive cesium was efficiently diluted by meso-scale eddies in the Kuroshio Extension region and its concentration in the surface, intermediate, and deep layers had already been reduced to the pre-Fukushima background value in the wide area within the North Pacific 2.5 years after the Fukushima disaster.

1. Introduction

Anthropogenic radionuclides such as Iodine-131 (^{131}I), Cesium-134 (^{134}Cs), and Cesium-137 (^{137}Cs) were accidently released into the ocean when the Fukushima Daiichi nuclear power plant (FNPP1) (Fig. 1) operated by Tokyo Electric Power Company (TEPCO) was damaged by the 9.0 magnitude Tohoku earthquake and the resulting tsunami on March 11, 2011. Oceanic monitoring performed immediately after the disaster detected unprecedentedly high radionuclide concentrations in the seawater around Fukushima Prefecture. As a result, researchers have conducted numerical analyses and oceanic surveys to determine the release amounts, concentrations, and migration processes of the radionuclides in the ocean (Kawamura et al., 2011; Buesseler et al., 2012; Honda et al., 2012; Miyazawa et al., 2012; Tsumune et al., 2012).

It is crucial to accurately determine the amounts of radionuclides discharged into the ocean and atmosphere in order to assess the effects on the marine environment. Kawamura et al. (2011) successfully constructed the time series of the ^{131}I and ^{137}Cs amounts discharged directly into the ocean between late March and late April 2011 using oceanic monitoring data obtained at the FNPP1 site. On the other hand, determining the amounts of airborne radionuclides deposited at the sea surface using oceanic monitoring data is complicated; thus, atmospheric dispersion models have frequently been adopted in previous studies (Kawamura et al., 2011; Honda et al., 2012). The Nuclear and Industrial Safety Agency (NISA) determined that 160 and 15 PBq (1 PBq = 10^{15} Bq) of ^{131}I and ^{137}Cs, respectively, were discharged into the atmosphere because of the Fukushima disaster. Meanwhile, TEPCO estimated that approximately 2.8 and 0.94 PBq of ^{131}I and ^{137}Cs, respectively, were discharged into the ocean during 120 h from April 1 to April 6, 2011. It was assumed in this study that equal amounts of ^{134}Cs and ^{137}Cs were released, because the radioactivity ratio of ^{134}Cs to ^{137}Cs in the seawater was approximately 1 to 1 (TEPCO, 2011a,b; Honda et al., 2012). Although ^{131}I (8.1 d half-life) decayed efficiently as compared to the radioactive cesium, the large amount of ^{131}I released made it important to assess the short-term effects on humans and the environment. On the other hand, radioactive ^{134}Cs (2.1 y half-life) and ^{137}Cs (30.1 y half-life) could have the significant long-term effects on the oceanic environment.

* Corresponding author. 2-4, Shirakata-Shirane, Tokai-mura, Naka-gun, Ibaraki, 319-1195, Japan. Tel.: +81 29 282 5170; fax: +81 29 282 6760.
E-mail address: kawamura.hideyuki@jaea.go.jp (H. Kawamura).

http://dx.doi.org/10.1016/j.jenvrad.2014.05.005
0265-931X/

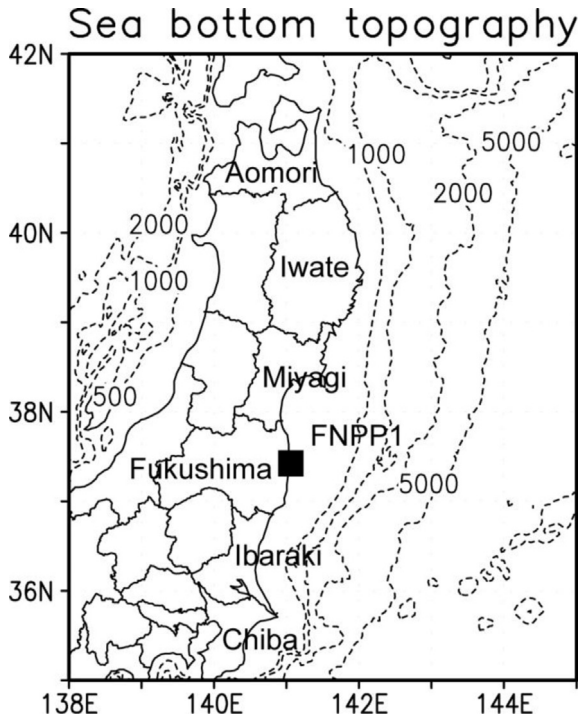

Fig. 1. Sea bottom topography (m) near Fukushima Prefecture. The black closed square indicates the FNPP1 location.

A realistic reproduction of oceanic conditions such as ocean current, temperature, salinity, and sea surface height (SSH) is critical for performing accurate numerical simulations on the oceanic dispersion of radionuclides. It is noticeable that the data assimilation technique coupling numerical models and observational data has been developed by oceanographers. Usui et al. (2006) constructed the three-dimensional variational (3D-VAR) data assimilation system, Meteorological Research Institute (MRI) Multivariate Ocean Variational Estimation (MOVE) with the eddy-resolving ocean general circulation model, MRI Community Ocean Model (MRI.COM; Tsujino et al., 2010) at the Japan Meteorological Agency (JMA). In this study, it is an important characteristic to utilize the accurately reanalyzed ocean current provided by MOVE, which was beneficial for simulating radionuclide migration especially by the Kuroshio Extension and its accompanying meso-scale eddies. This study aims to determine the concentrations and migration processes of the long-lived radionuclides, ^{134}Cs and ^{137}Cs, released from FNPP1 in the North Pacific over a period of about 2.5 years after the Fukushima disaster.

2. Model description

2.1. Atmospheric dispersion model

Estimation of the airborne radioactive cesium amounts deposited at the North Pacific sea surface was necessary to implement the numerical simulations. We adopted the Worldwide Version of System for Prediction of Environmental Emergency Dose Information (WSPEEDI-II) (Terada et al., 2008) developed at the Japan Atomic Energy Agency (JAEA) to calculate the ^{134}Cs and ^{137}Cs deposition amounts in the North Pacific from March to May 2011. WSPEEDI-II consists of the non-hydrostatic meso-scale meteorological prediction model MM5 (Grell et al., 1994) and particle random-walk model GEARN developed at JAEA (Terada and Chino, 2008) that can calculate the surface deposition on the land and ocean by incorporating dry and wet deposition processes, air concentrations, and radiological doses. Meteorological elements such as wind and precipitation can be predicted using MM5 along with the numerical forecast data (GSM-Global) provided by JMA and National Centers for Environmental Prediction (NCEP) Reynolds optimally interpolated weekly sea surface temperature (SST) data as the initial and boundary conditions. The atmospheric radionuclide dispersion is subsequently calculated using GEARN with meteorological elements as input variables, followed by the meteorological prediction. See Terada et al. (2004), Furuno et al. (2004), and Terada and Chino (2005, 2008) for more details on WSPEEDI-II and its prediction performance. A large portion of the airborne radioactive cesium may have fallen on the land and ocean during the first few months following the Fukushima disaster. Therefore, we conducted the atmospheric dispersion simulations from 20 UTC on March 11 to 0 UTC on June 1, 2011. The model domain is nearly the entire North Pacific with horizontal resolutions of 10 km in the latitudinal and longitudinal directions.

A source term describing the radioactive materials discharged into the atmosphere because of the Fukushima disaster is still a controversial issue for atmospheric dispersion simulations. Chino et al. (2011) successfully constructed the realistic time series for the ^{131}I and ^{137}Cs release amounts from March 12 to April 6, 2011, using WSPEEDI-II, dust sampling data, and air dose rate data. They concluded that the ^{131}I and ^{137}Cs amounts released into the atmosphere from 10 JST (Japanese Standard Time, JST = UTC + 9 h) on March 12 to 0 JST on April 6, 2011 were approximately 150 and 13 PBq, respectively. Their source term, according to Terada et al. (2012), had been refined and extended to May 1, 2011, in order to correct the significant discrepancies between the simulated and measured daily surface depositions on the land and incorporate new available environmental monitoring data. Kobayashi et al. (2013) further refined the amounts of the radionuclides released into the atmosphere based on those estimated by Terada et al. (2012), using oceanic monitoring data. We adopted the time series of the ^{137}Cs release amount estimated by Kobayashi et al. (2013) as the source term for our atmospheric dispersion simulation. We assumed that the ^{134}Cs release amount was the same as the ^{137}Cs release amount owing to the fact that the radioactivity ratio of ^{134}Cs to ^{137}Cs on oceanic monitoring data obtained shortly after the Fukushima disaster was approximately 1:1.

2.2. Oceanic dispersion model

MOVE developed at MRI, JMA includes the western North Pacific version (MOVE-WNP) and North Pacific version (MOVE-NP). It statistically performs optimized prediction on the 3D-VAR data assimilation equipped with MRI.COM and analysis scheme by combining the model and observations. The satellite data on SSH and SST and in-situ temperature and salinity profiles are assimilated in MOVE. The model domain for MOVE-WNP extends from 15°N to 65°N and 117°E to 160°W. It employs variable horizontal grid resolutions, i.e., 1/10° from 15°N to 50°N and 1/6° from 50°N to 65°N, and 1/10° from 117°E to 160°E and 1/6° from 160°E to 160°W, in order to reproduce the meso-scale phenomena that frequently appear along with the Kuroshio Current and Kuroshio Extension in the western North Pacific. MOVE-WNP is the inner system in MOVE-NP and it is nested by replacing the oceanic variables at lateral boundaries with the predicted ones from MOVE-NP, which covers the Pacific Ocean north of 15°S with horizontal resolutions of 1/2° in both the latitudinal and longitudinal directions. With respect to a vertical resolution, 54 levels are set with vertically-varying level thickness ranging from 1 m at the sea surface to 600 m near the deepest part in MOVE-WNP and MOVE-NP.

In this study, we used the finite difference model SEA-GEARN-FDM which was developed based on the particle random-walk