Assessment of the radiation doses to the public from the cesium in oceans after Fukushima Nuclear Accident

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ABSTRACT

A great number of radioactive cesium were released into sea water after Fukushima Accident. We modified the Regional Oceanic Modelling System (ROMS) to reproduce the dispersion process of the cesium in oceans. The simulated water concentration was in good agreement with observation. In order to explore the nuclear impact of these contaminant in ocean, we established a food web model to calculate the concentration in marine organisms and assess the internal dose rate to the public. The estimated internal dose rate is small compared with the recommended limit by International Atomic Energy Agency (IAEA). Then, we employed the Monte Carlo N Particle Transport Code (MCNP) to calculate the transfer coefficient. The external dose rate could be estimated by this coefficient and simulated water concentration.

Keywords

Fukushima NPP, numerical simulation, ROMS, radiation dose.

INTRODUCTION

On March 11th 2011, an M9.0 earthquake and tsunami destroyed the cooling system of the Fukushima Daiichi nuclear power plant (FDNPP) with the subsequent tsunami. In order to prevent the core meltdown, the Tokyo Electric Power Company (TEPCO, the owner of FDNPP) used seawater to cool down the overheating reactors, which caused a great number of radionuclides discharged into the Pacific Ocean. Some researchers estimated that the cesium-137 released into the ocean was more than 10^{16}Bq(Lai et al., 2013; Rypina, Jayne, Yoshida, Macdonald, Douglass and Buesseler, 2013) and the amounts of cesium-134 were in the same level. Therefore, it is necessary to estimate the radiation dose from these nuclides to the public.

Numerical simulation is a good option to solve this problem. In this paper, we employ the ROMS (Hedström, 2012; Shchepetkin and McWilliams, 2005) to reproduce the circulation of the ocean around Japan and establish a new module to simulate the dispersion process of radionuclides in the ocean. Then, the internal and external dose rate were assessed, respectively.

MODEL CONFIGURATION

We build a one-way nested model to simulate the circulation. The parent domain covers the coastal region of China and entire oceanic area around Japan (121°E-161°E, 23°N- 45°N). The horizontal resolution is about 9km with 400x268 meshes in zonal and meridional directions, respectively. The child domain covers the east region of Honshu and has about 3km horizontal resolution with 396x270 meshes. The S-coordinate is employed in vertical and the vertical discretization is

30 layers. HYCOM + NCODA Global 1/12° Analysis (GLBu0.08)(Chassignet et al., 2007) is used to calculate the initial file and boundary file for the parent domain. And the sea surface momentum stress, heat flux and freshwater flux were calculated from Global Forecast System (GFS)(National Oceanic and Atmospheric Administration, 2013) system.

In order to simulate the dispersion process of radionuclides, we modified the tracer equation and added the decay and scavenging processes which is the removal of nuclides by absorption onto suspended materials that deposit by on the sea floor by sedimentation (Tsumune, Aoyama and Hirose, 2003), as follows:

$$\frac{\partial(H_z C)}{\partial t}+\frac{\partial(uH_z C)}{\partial x}+\frac{\partial(vH_z C)}{\partial y}+\frac{\partial(\Omega H_z C)}{\partial \sigma}= \frac{\partial}{\partial \sigma}\left(\frac{K_C}{H_z}\frac{\partial C}{\partial \sigma}\right)+H_z\left(F_C+D_C\right)-\lambda H_z C-K_d\rho_s(z)w_s\frac{\partial C}{\partial \sigma} \quad (1)$$

where C is the concentration; u,v,Ω are the velocity in x,y,σ direction; F_C is the source term; D_C represents the horizontal diffusive term; λ is the decay coefficient ($\lambda_{137}=7.33\times10^{-10}$ s^{-1}; $\lambda_{134}=1.07\times10^{-8}$ s^{-1}). The last term in equation (1) stands for the scavenging processes. K_d is the distribution coefficient of the nuclides; ρ_s is the concentration of the suspended materials; and w_s represents the settling velocity.

VALIDATION

Firstly, we validate the effectiveness of the simulated physical fields. The archiving, validation and interpretation of satellite oceanographic data (AVISO) is applied as observed data to validate the sea surface height (SSH) of our model. Three criteria were used: correlation, mean of differences and standard deviation of differences, as shown in Figure 1. The axis on the left is for the correlation which is non-dimensional and the axis on the right is for the mean/standard deviation of differences whose units are meter.

In the three simulated years, the correlation between simulation and observation is high. The mean of differences is around zero all the time and the standard deviation is low. Therefore, we could conclude that our model could reproduce the circulation successfully.

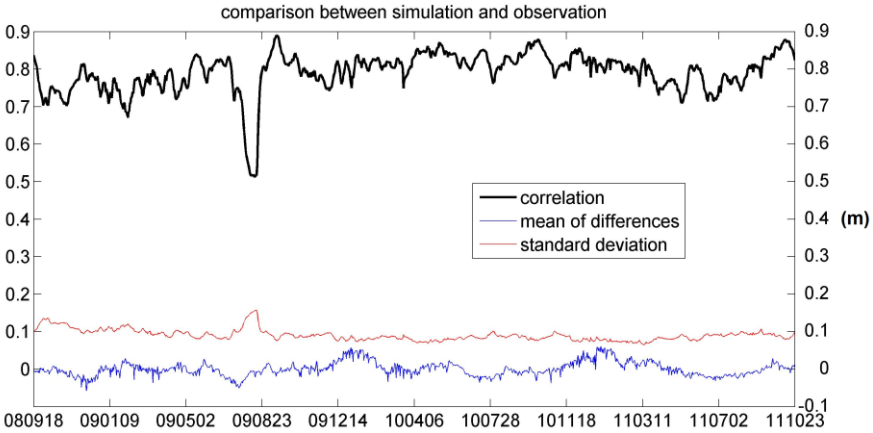

Figure 1. The time series of correlation between simulated SSH anomalies and AVISO SSH anomalies (black); mean (blue) and standard deviation (red) of differences

Secondly, we compared the simulated concentration of ^{137}Cs in sea surface with the observed data from TEPCO. We employed three criteria to quantify the performance of the simulation: Root Mean Square of Logarithm of Ratio (RMSLR), FAC3 and FAC10. The definition of them are as follows:

$$RMSLR=\sqrt{1/n\sum_i^n\left[\log_{10}(C_s/C_o)\right]^2} \quad (2)$$

$$FAC3=\text{fraction of data that satisfies } \frac{1}{3}\le\frac{C_s}{C_o}\le 3 \quad (3)$$

$$FAC10=\text{fraction of data that satisfies } \frac{1}{10}\le\frac{C_s}{C_o}\le 10 \quad (4)$$

Where, C_s stands for the simulated concentration and C_o represents the observed concentration. The results of the criteria are summarized in Table 1. "F1N", "F1S", "F2" and "Iwasawa" represent the four observation stations from TEPCO. On the basis of the definition, it means that the average difference between simulation and observation is 3.16 times if RMSLR is 0.5 and 10 times if RMSLR is 1. In table 1, the small RMSLR and large FAC3/FAC10 mean that the simulated concentration could reproduce the observed sea surface concentration. Table 1 demonstrates that our model could reproduce the dispersion process of radionuclides in oceans very well.

	RMSLR	FAC3	FAC10
F1N	0.3880	81.1%	98.3%
F1S	0.3842	80.9%	99.4%
F2	0.5732	55.7%	92.9%
Iwasawa	0.7635	45.2%	79.5%

Table 1. The Criteria between Simulated Concentration and Observation

INTERNAL DOSE RATE

There are two main pathways by which the radionuclides might have nuclear impact on the public: the internal and the external. The internal dose rate comes from ingestion of sea food collected in the ocean (Maderich et al., 2014; Nakano and Povinec, 2012). It is calculated by the following equation:

$$DR^{\text{int}} = \sum_i DC_i \sum_k C_{i,k} \cdot Intake_k \quad (5)$$

Where, the DR^{int} represents the internal dose rate (Sv/year); $C_{i,k}$ stands for the concentration of nuclide i in the marine product k (Bq/kg); DC_i is the dose coefficient(ICRP, 1995) (Sv/Bq) and $Intake_k$ represents the average intake rate(Nakano and Povinec, 2012) of the public (kg/year). In order to calculate $C_{i,k}$, we established a model based on the food web. We grouped marine organisms into phytoplankton, zooplankton, crustaceans, mollusks, fish and macroalgae. The variation of concentration in marine organisms are based on equation (6).

$$\frac{dC_{i,k}}{dt} = v_{i,k}^{food} C_{i,k}^{food} - (v_{i,k}^{el} + \lambda_k) C_{i,k} \quad (6)$$

v^{el} is the elimination rate (day^{-1}); v^{food} represents the uptake rate (day^{-1}); C^{food} is the concentration in the prey organism. The elimination rate could be found in other researches (Vives I Batlle et al., 2014). Recently, International Atomic Energy Agency (IAEA, 2014) provides the recommended values of equilibrium concentration ratios (*CR*) for different organisms and different nuclides. On the basis of *CR* in equilibrium, we calculated the uptake rate as shown in Table 2. The concentration in phytoplankton was calculated from multiply the concentration in water by CR_{phy}, because the rapid uptake/elimination process.

	Fish	Crustaceans	Macroalgae	Mollusks	Zooplankton
v^{el}	0.01071	0.01206	0.01284	0.03851	0.05173
v^{food}	6.92×10^{-3}	0.00604	1.232	0.0587	0.7912

Table 2. The Elimination and Uptake Rate of Cesium (day^{-1})

Figure 2 shows the time series of concentrations in different marine organisms based on our model and the equilibrium concentration rate. The concentration in water is the observation data from TEPCO.

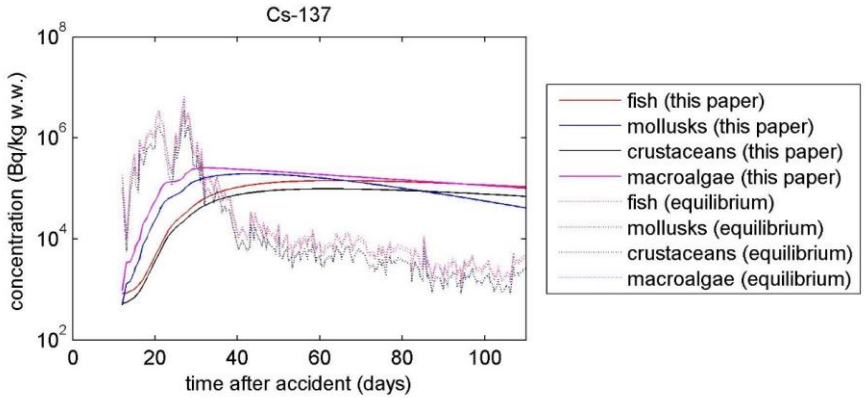

Figure 2 The concentration in marine organisms in the north canal of FDNPP based on our model and equilibrium method

In equilibrium methods, concentrations in all organisms varied with the concentration in water. The oscillation is obvious, which is apparently unpractical. In our model, however, the concentration of predator organisms shows time lag and has smoother variation, because of the food web model. Figure 2 suggests very different results from equilibrium and our dynamic model. We calculated the average total dose rates to macroalgae at Iwasawa shore and Daini NPP north channel stations (two observation stations from TEPCO) based on both models. The equilibrium model predicts the dose rate could be 1.6×10^{4}μSv/h, while the dynamic model shows the dose rate would be 1.5μSv/h. The mean monitoring data in the corresponding region is $1.3\pm0.5\times10^{-1}$μSv/h (Vives I Batlle et al., 2014). It is obvious that our model is more effective than the equilibrium model.

On the basis of equation (6) and the simulated water concentration, we calculated the concentrations in marine organisms. We choose three fishing places to assess the internal dose rate: one is located in the vicinity of FDNPP, the second one is around the coast of Ibaraki Prefecture (next to Fukushima Prefecture); the last is in Chiba Prefecture. Table 3 shows the internal dose rate to the public from the ^{137}Cs and ^{134}Cs in sea water. There are two hypothetical cases: we calculated the time series of the concentrations in every organism. The maximum concentration and the yearly average concentration were used in equation (5) and obtained the two types of assessment of internal dose rate to the public

Fishing places	Fukushima		Ibaraki		Chiba	
	Maximum	Yearly mean	Maximum	Yearly mean	Maximum	Yearly mean
^{137}Cs	0.544	0.204	0.060	0.023	0.0010	0.0004
^{134}Cs	0.755	0.268	0.081	0.030	0.0013	0.0005
Total	1.299	0.472	0.141	0.053	0.0023	0.0009

Table 3. The lnternal Dose Rate from Different Fishing Places (mSv/year)

As shown in Table 3, the maximum estimation could peak to 1.3mSv/year, which is in good agreement with some others' assessment (Maderich et al., 2014). However, this is the worst case, which means all the marine products ingested by someone were collected in the fishing place nearest to FDNPP and all of these products were collected when they had the maximum concentration. If the product are collected in the Ibaraki Prefecture fishing places, the internal dose rate would be 53-141 μSv/year. And the dose rate would decrease to only 0.9-2.3μSv/year if the marine products were collected in fishing places in Chiba Prefecture. Therefore, we found the estimated internal dose rate originated from the radioactive cesium was much lower than the limit to the public recommended by IAEA (1 mSv/year), if the marine products were not collected in the vicinity of FDNPP.

Figure 3 shows the distribution of average internal dose rate in the east of Honshu. The dose rate originated from seafood ingestion is around 1 μSv/year in most region. Therefore, if the marine product consumed by the public was collected in these area, the internal dose rate is small. The Kuroshio Current acts as a barrier (Behrens, Schwarzkopf, Luebbecke and Boening, 2012) and barricades the southward dispersion of radioactive cesium which could explain the less dose rate in the south.

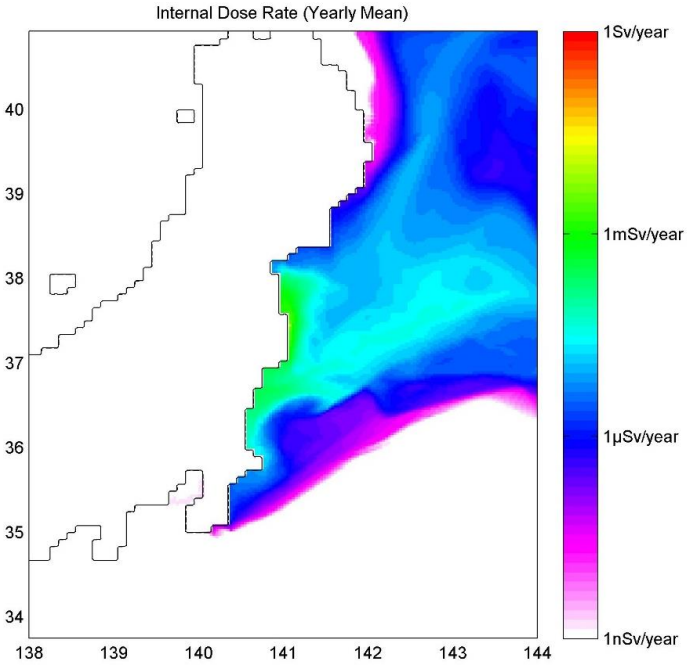

Figure 2 The spatial distribution of yearly average internal dose rate

EXTERNAL DOSE RATE

We employed the Monte Carlo N Particle Transport Code (MCNP) to estimate the external dose rate. A human model floats in the contaminated sea water and the effective dose rate from cesium is simulated. The detailed method was described elsewhere (Guan, Shen and Huang, 2015). We conclude that in every hour, a person would accept 1.98×10^{-10} Sv effective dose if he/she immersed in 1 Bq/L ^{137}Cs sea water. As for ^{134}Cs, the relation coefficient is 4.19×10^{-10} Sv h^{-1} for 1 Bq/L concentration sea water. The observed concentration of cesium in sea surface could peak to 10^4 Bq/L, which means immersing in those water would accept more than 1 μSv h^{-1} external dose rate. But the dose rate would decrease rapidly with the distance from FDNPP or the time elapse.

CONCLUSION

We modified ROMS to simulate the dispersion process of nuclides released from the FDNPP in ocean. The simulated water concentration of cesium were in good agreement with observation.

On the basis of the temporal and spatial distribution of water concentration, a food web model was established to assess the cesium concentration in marine organisms. Then, the internal dose rate to the public is estimated. Finally, the MCNP model is employed to calculate the transfer coefficient. The external dose rate could be estimated by the coefficient and water concentration.

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