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Applications of Radiocesium Migration Models to Fukushima Environmental Issues: Numerical analysis of radiocesium transport in temperature-stratified reservoirs by 3D-Sea-SPEC

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Abstract

Some of radiocesium released into the surrounding environment by the accident of the Fukushima Dai-ichi Nuclear Power Plant fell on the ground, and most of them was adsorbed by soil particles. Therefore, soil particles are main carrier of radiocesium, whose outflow rate from the land to rivers is known to be limited less than one percent per year. In this paper, we thus simulate sediment flow dynamics during a flood event in a large reservoir filled with temperature-stratified water by using a three-dimensional simulation code and reveal characteristic migration behaviors of sediment-sorbed radiocesium in the reservoir system. Adding a correction scheme to accurately handle heat transport in the reservoir water, we successfully reproduce water temperature stratification seen normally in summer season. Then, we find that most of the clay particles flowing into a temperature-stratified reservoir stays only in the upper layer, suggesting its peculiar transport dynamics of radiocesium in summer season.

1. Introduction

A large amount of radiocesium was released into the surrounding environment by the accident of the Fukushima Dai-ichi Nuclear Power Plant occurred in 2011, and some of them fell on the ground over Fukushima Prefecture. Since cesium is an alkali metal element with a relatively large ionic radius, it is strongly adsorbed by soil particles, especially clay ones [1,2]. Thus, the movement of radiocesium is mostly dominated by that of clay particles, which is driven by the rain water flow. In order to reveal the transport of radiocesium on the ground, it is of great importance to understand the behavior of cesium-sorbed clay particles in fresh aquatic systems such as rivers and reservoirs [3-7]. However, the water flow in rivers is not so simple, and the flow of temperature-stratified water as observed on large reservoirs during summer is more complicated.

One of the powerful schemes to unveil such complex transport is computer simulation. Thus, we have developed 3-dimensional fluid simulation code named "3D-Sea-SPEC" (3D Sea Simulation for Port and its Environmental Coast). The code can take into account the water temperature by solving the heat transport equation under σ-coordination system commonly used in aquatic environments. However, it has been known for its usual code implementations to be difficult to reproduce and keep the water temperature stratification. Therefore, we improve the code and demonstrate the flow dynamics of the temperature-stratified water in a large reservoir, which is typical for highly-contaminated Fukushima area.

In this paper, we give an overview of 3D-Sea-SPEC and explain an improvement scheme to realize the water temperature stratification. Next, we actually apply the improved one to a reservoir filled by inflow of water from a river, and we examine the behavior of the suspended sediment in the reservoir by changing the temperatures in the inflow river water.

2. Simulation code

2.1 Overview of 3D-Sea-SPEC

In dam reservoirs, not only horizontal but also vertical water flow significantly influences the flow field dynamics. Therefore, we should utilize a 3D simulation code to evaluate the water flow and behaviors of suspended sediments in these aquatic systems. A 3D simulation code using a simple orthogonal coordinate system (generalized coordinate system) is frequently employed to simulate the evolution dynamics in 3D. However, when using such simple coordinate systems for the typical slope shapes with steep gradients usually seen in small reservoirs in Japan, the bottom water flow is then known to be simulated inadequately with appearance of computational artifacts. Therefore, we have developed a 3D water-flow simulation code, called 3D-Sea-SPEC (3D Sea Simulation for Port and its Environmental Coast) by employing the dual-sigma coordinate system to avoid such artifacts [8,9]. Although 3D-Sea-SPEC was originally developed for the simulation for transport of radionuclide inside coastal structures like ports and coasts, this code can be applied for rivers and dam reservoirs by setting the salinity to be zero. The simulation system inside the reservoir is set up by separating the water column into an upper layer and a lower layer, and dividing each internal layer into cells with equal size. The upper and the lower layers adjust for the changes in water surface level and steep bottom topography, respectively.

2.2 Simulation for temperature-stratified water in reservoir

The 3D simulation code (3D-Sea-SPEC) adopts the dual-sigma coordinate system along the vertical direction and the orthogonal coordinate system in the horizontal direction, respectively. The code calculates the dynamics of water flow velocity and water depth by solving the following equations.

- Equation of continuity

$$\frac{\partial D}{\partial t} + \frac{\partial (Du)}{\partial x} + \frac{\partial (Dv)}{\partial y} + \frac{\partial w^*}{\partial \sigma} = 0 \tag{1}$$

- Equations of motion

$$\frac{\partial (Du)}{\partial t} + \frac{\partial (Du^2)}{\partial x} + \frac{\partial (Dvu)}{\partial y} + \frac{\partial (w^* u)}{\partial \sigma} - fvD = -D\left\{\frac{1}{\rho}\frac{\partial p}{\partial x} + g\left((1+\sigma)\frac{\partial D}{\partial x} - \frac{\partial H}{\partial x}\right)\right\} + \frac{\partial}{\partial x}\left(A_x D\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(A_y D\frac{\partial u}{\partial y}\right) + \frac{\partial}{\partial \sigma}\left(\frac{A_z}{D}\frac{\partial u}{\partial \sigma}\right) \tag{2}$$

$$\frac{\partial(Dv)}{\partial t}+\frac{\partial(Duv)}{\partial x}+\frac{\partial(Dv^2)}{\partial y}+\frac{\partial(w^*v)}{\partial\sigma}+fuD=-D\left\{\frac{1}{\rho}\frac{\partial p}{\partial y}+g\left((1+\sigma)\frac{\partial D}{\partial y}-\frac{\partial H}{\partial y}\right)\right\}$$
$$+\frac{\partial}{\partial x}\left(A_xD\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial y}\left(A_yD\frac{\partial v}{\partial y}\right)+\frac{\partial}{\partial\sigma}\left(\frac{A_z}{D}\frac{\partial v}{\partial\sigma}\right), \quad (3)$$

where D is the total water depth (from the surface to the bottom), t the time, p pressure, u, v, and w^*, velocity in the x-, y-, and σ-direction, g gravitational acceleration ($9.8m/s^2$), ρ density of water, H water level (the elevation of the surface of the water), A the eddy viscosity coefficient, and f the Coriolis coefficient, respectively. When calculating these equations, we assign the variables on the 3D staggered grid. Then, we calculate the vertical diffusion by using an implicit solver to achieve a stable execution of the simulation. In addition, our code simulates the suspended sediment transport by using the following equation:

$$\frac{\partial RD}{\partial t}+\frac{\partial}{\partial x}(uRD)+\frac{\partial}{\partial y}(vRD)+\frac{\partial}{\partial\sigma}(wR)=$$
$$\frac{\partial}{\partial x}\left(DK_x\frac{\partial R}{\partial x}\right)+\frac{\partial}{\partial y}\left(DK_y\frac{\partial R}{\partial y}\right)+\frac{\partial}{\partial\sigma}\left(\frac{K_z}{D}\frac{\partial R}{\partial\sigma}\right)-S_v\frac{\partial R}{\partial\sigma}+R_{up}+R_{in}\ , \quad (4)$$

where R is the suspended sediment concentration, K dispersion coefficient (the subscription has the same meaning as above), R_{up} and R_{in} the amounts of suspended sediments supplied from riverbeds and boundaries, respectively, and S_v the settling velocity of suspended sediment given by Stokes' law.

2.3 Simulation for temperature-stratified water in dam reservoir

3D-Sea-SPEC code uses the sigma coordinate system. Since the water column is equivalently discretized everywhere, the cell size along the vertical direction varies adjusting to the water depth Therefore, it is not simple to accurately simulate the horizontal movement of heat energy, and therefore, it is eventually impossible to reproduce and keep the water temperature stratification within the standard code implementation. In order to resolve this problem, we add a vertical interpolation scheme to calculate horizontal heat energy transport and pressure accurately under the sigma coordinate system into 3D-Sea-SPEC (see Fig. 1 in details) [10,11]. The present scheme is just a way to adjust horizontal transport including certain vertical components due to the sigma coordinate system. However, we note that this scheme is essential for reservoir systems with relatively steep bottom-topography typically seen in Japan.

We actually simulate water temperature in a dam reservoir shown in Fig. 2 by using 3D-Sea-SPEC on 48 cores of SGI ICE X in JAEA to confirm the validity of the scheme. Our target region is an approximately 2 km × 2 km area. We divided the area into 202 × 175 cells. Each grid area is 10 m × 10 m. The initial condition of water temperature and the water inflow data are given by Fig. 3 and Table 1. Here, the water temperature of an inflow river is set to be 25 °C. Fig. 4 shows the water temperature distribution 36 hours passed with/without the correction scheme. The result indicates that the temperature stratification is not maintained without the scheme. As a result, we conclude that the correction scheme is crucial in reproducing and keeping the temperature stratification.

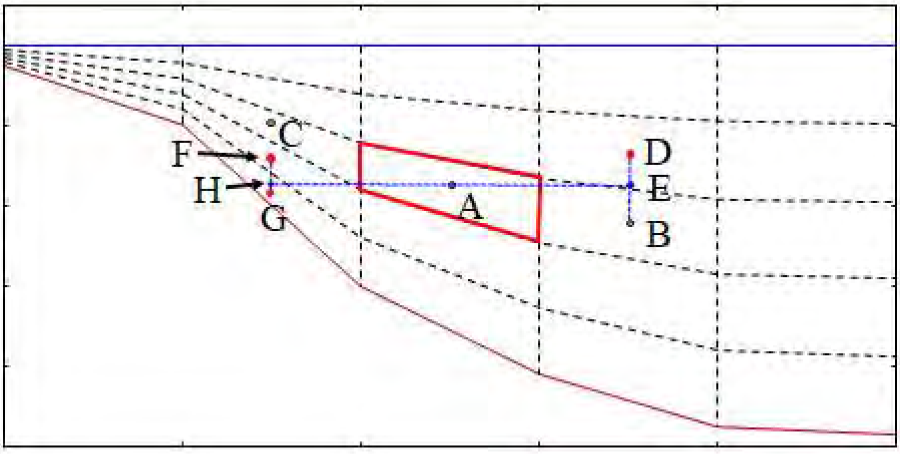

Figure. 1 An interpolated scheme to accurately calculate heat energy along the horizontal direction. All the variables inside a cell surrounding by the red line are defined at point A. Note that those of the horizontally neighbor cells are formally given at point B and C, respectively. Thus, the horizontal transport from B to A or C to A always contains certain vertical components. Then, the horizontal transport should be defined in E to A and H to A, in which E and H are given by the interpolation scheme between B and D and G and F, respectively.

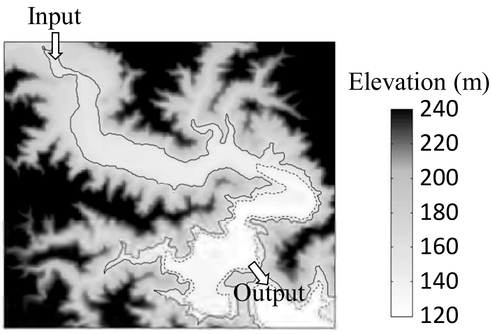

Figure 2. Shape of a dam reservoir in the present simulation. The dashed and the solid lines indicate contour lines showing water edges in cases of 140 m and 160 m water-elevation heights, respectively.

Table 1. Water inflow.

Hours	Inflow (m^3/sec)
0 --> 2	5 --> 20
2 --> 12	20
12 --> 14	20 --> 5
14 -->	5

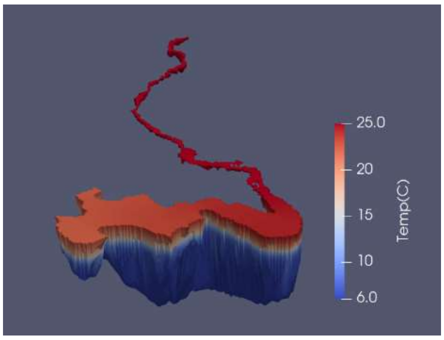

Figure 3. Initial distribution of water temperature of the target dam reservoir. Its water temperature is stratified.

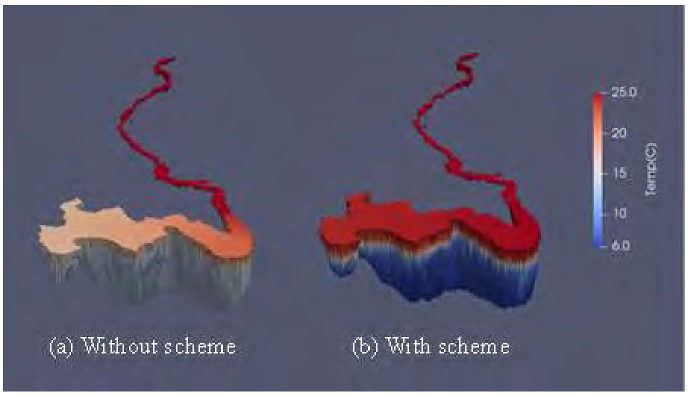

Figure 4. Simulation result of water temperature distribution with/without the correction scheme.

3. Simulation for temperature-stratified water in dam reservoir

In this section, we simulate the water flow dynamics in a large dam reservoir, into which a river water flows, by using 3D-Sea-SPEC with the interpolating scheme along the horizontal direction. Here, the initial state of the dam reservoir is set to a stratified water-temperature profile as shown Fig. 3, and the temperature of the inflow river is given in three cases as 25 °C, 10 °C, and 5°C. Moreover, the inflow water is supposed to contain clay (particle size: 2.4μm) and silt (36μm) whose quantities are proportional to the flow rate volume. The results of water temperature distribution after 36 hours passed are shown in Fig. 5. The figures indicate that the water stratification maintains at 25 °C, but it is destroyed at 5 °C. In the case of 10 °C, the stratification is also destroyed.

Next, we show the results of the clay and silt distributions after 36 hours passed in Fig. 6 and 7, respectively. The results at 25 °C demonstrate that clay particles remain in the upper layer, but silt ones are mixed vertically. This is due to the difference in settling velocity between clay and silt particles. In the present simulation, the settling velocity of clay and silt ones given by Stokes' law are $1.159 \times 10^{-5}\mathrm{m/sec}$ and $8.512 \times 10^{-4}\mathrm{m/sec}$, respectively. Therefore, clay and silt ones sink about 1 m and about 74 m per day, respectively. Therefore, in the case of 25 °C, silt ones spread over the upper layer with river water, and then, it spreads vertically (see Fig. 8). On the other hand, the results of the silt distributions at 10 °C and 5 °C shown in Fig. 7 and 8 indicate that the silt ones pass while spreading throughout the middle layers, and then, it sinks vertically in a certain level.

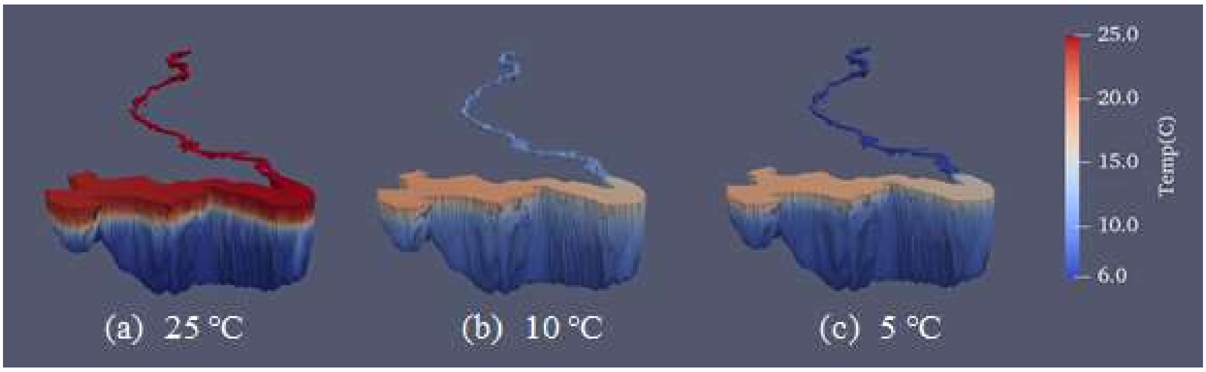

Figure 5. Water temperature distribution after 36 hours passed.

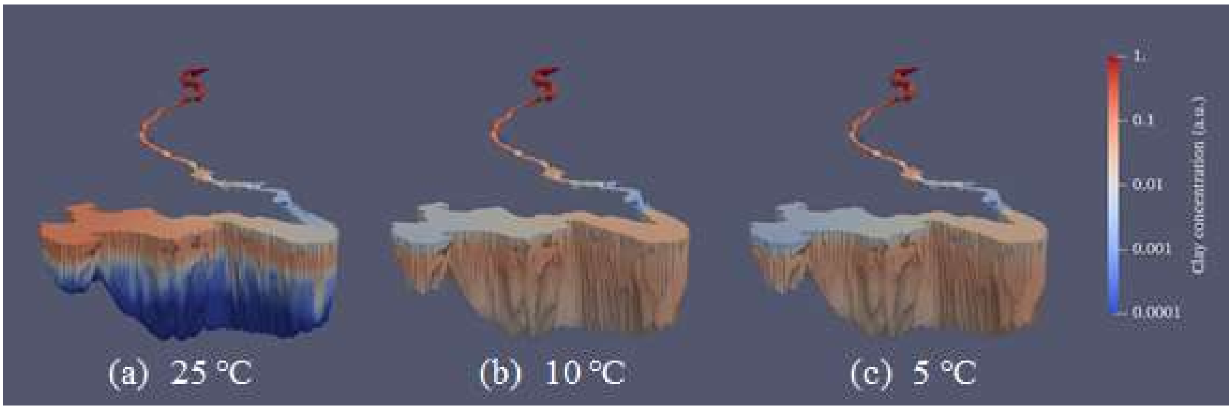

Figure 6. Clay concentration distribution after 36 hours passed.

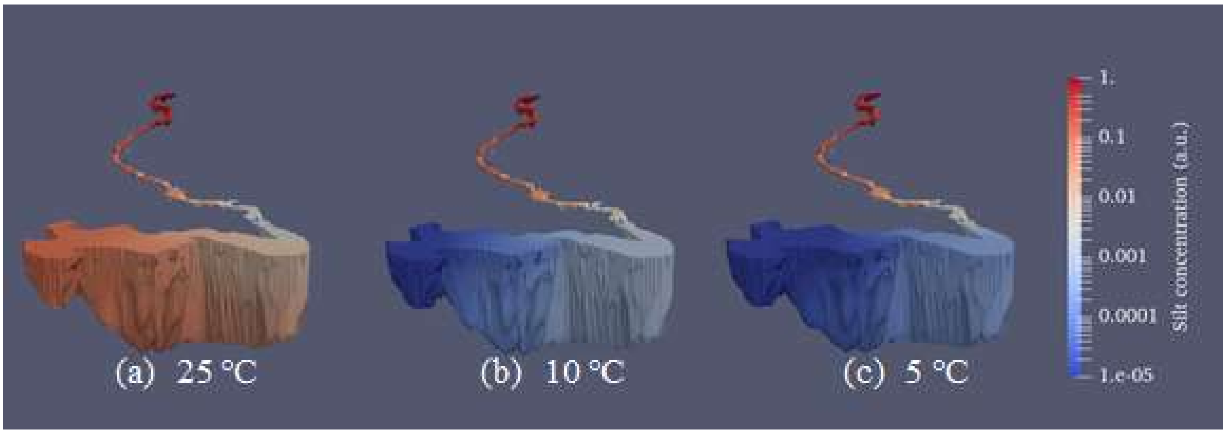

Figure 7. Silt concentration distribution after 36 hours passed.

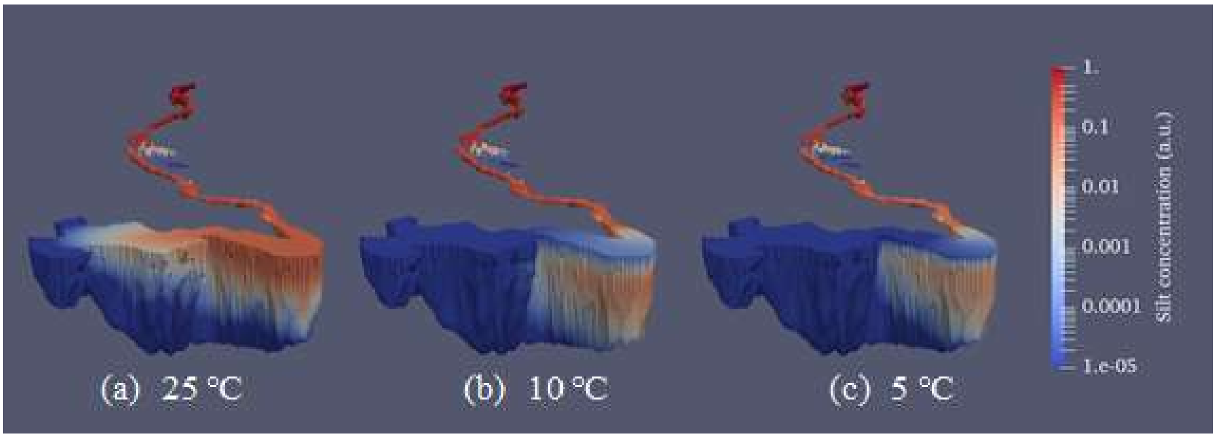

Figure 8. Silt concentration distribution after 5 hours passed.

4. Conclusions

We examined behaviors of radiocesium by simulating sediment dynamics in a dam reservoir with temperature-stratified water, because cesium is strongly adsorbed by soil particles. Since our simulation code 3D-Sea-SPEC employs the sigma coordinate system, it has a serious problem in horizontal transport of heat energy and other ones. Therefore, we adopted the correction scheme to accurately calculate the horizontal transport by interpolating the grid cell. We simulated the flow of temperature-stratified water in a large dam reservoir using 3D-Sea-SPEC with the correction scheme. The result show that when the temperature of river water is sufficiently high, temperature-stratification is maintained and clay particles supplied by the river water remain inside the upper layer. Moreover, it is demonstrated that silt particles spread over the upper layer with river water while they move vertically in a certain level.

In this research, we assumed that cesium is irreversibly adsorbed by soil particles. However, in reality cesium can be desorbed from soil particles depending on its environment. In the future, we will improve our simulation by taking into account such effects.

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