Progress in NUCLEAR SCIENCE and TECHNOLOGY, Vol. 1, p.420-423 (2011)

ARTICLE

The Simulation of long-range transport of ^{137}Cs by yellow sand phenomena in East Asia

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In early spring of the past decade, depositions of ^{137}Cs have been increasing along the coast of the Sea of Japan. The National Institute for Agro-Environmental Science (NIAES) measured the deposition of ^{137}Cs at the northwestern coastal area of Japan in 2006-2007 and concluded that most of this ^{137}Cs was wafted over Japan by san dstorms from China. The authors developed a system using long-range models of ^{137}Cs for simulation to find the amount of material transported. This system, which runs on Microsoft Windows, will help identify fallout from natural phenomena or human factors like nuclear accidents. The simulated depositions of ^{137}Cs from East Asia in March of 2006 were compared with measurements from two resources. One source was NIAES data from the yellow sand phenomena at Sado Island and the other source was the Environmental Radiation Database in Japan for mon thly deposition data throughout the country. The simulation reproduced the arrival of the peak deposition of ^{137}Cs at Sado Island and the results of normalized ^{137}Cs depositions correlated well with monthly deposition data from the database suggesting that the deposition of ^{137}Cs was transported from the East Asian continent by the yellow sand phenomena.

KEYWORDS: ^{137}Cs, dust model, kosa, yellow sand phenomena, atmospheric dispersion model, RAMS

I. Introduction

Environmental monitoring in Japan shows that radioactive nuclide concentration, deposition and ambient dose rates vary by season and by climatic events such as precipitation, thunderstorms, the yellow-sand phenomena, and other natural acts. It is a well established fact that dose rates of radon decay products increase with precipitation. Recently, ^{137}Cs deposition along the coast of the Sea of Japan in early spring has been increasing. For the sake of public safety, it is vital to ascertain whether this increase is caused by natural phenomena or nuclear mishap. The purpose of this study is to elucidate the mechanisms of ^{137}Cs change (transport, soil entrainment, and deposition) for distinction from human factors. According to measurements obtained by the Environmental Radiation Database in Japan in the 1960's, the monthly ^{137}Cs deposition was primarily due to nuclear testing conducted on the continent of East Asia. During the Chernobyl Nuclear Accident of 1986, ^{137}Cs deposition was measured at over 100mBq/m^2 in Japan. After the Chernobyl Accident in the 1990's, ^{137}Cs deposition decreased measuring at 0.1mBq/m^2. ^{137}Cs deposition measured at 1.64mBq/m^2 during March of 2002 in Tottori, and measured at about 1.0mBq/m^2 in Aomori. The National Institute for Agro-Environmental Science (NIAES) measured ^{137}Cs at the Northwestern coastal area of Japan in 2006-2007 and concluded that most of the ^{137}Cs deposited was transported by the yellow sand phenomena. In this study, the authors developed long-range transport models of ^{137}Cs considering the yellow sand phenomena. Through simulations, the authors explain the mechanisms of transportation and find the amount of transported materials.

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II. Modeling and Conditions

1. Outline

In developing the model, two systems were used: (1) RAMS4.4 (Regional Atmospheric Modeling System)[1)] which simulates a 3-D meteorological field, and (2) HYPACT1.2 (The RAMS Hybrid Particle and Concentration Transport Model)[1)] which calculates the transporting of ^{137}Cs from the results of RAMS. The dispersion model includes a dust model for evaluating the entrainment of sand and dust particles by the wind. The model outline as shown in **Fig.1**. is a two-nested grid structure that includes an East Asia region of 9,000 km x 5,600 km as the parent grid, and within the vicinity of Japan a 3,400 km x 2,000 km grid as the nest for high resolution. The vertical calculation extends to a height of 20 km. For meteorological data, NCEP/NCAR (National Centers for Environmental Prediction/The National Center of Atmospheric Research) re-analysis data was used. The sea surface temperature (SST) was from NCAR OI (ver.2) weekly data set (1 degree by 1 degree). The topographical and land use data was obtained from the United States Geological Survey (USGS). Surface characteristic data for evaluating threshold friction velocity was taken from the daily NDVI (Normalized Difference Vegetation Index) data from NOAA/AVHRR and ISLSCP Initiative II (The International Satellite Land-Surface Climatology Project, Initiative II) data set (1 degree by 1 degree) as the soil type. The calculation area is shown in **Fig.2**.

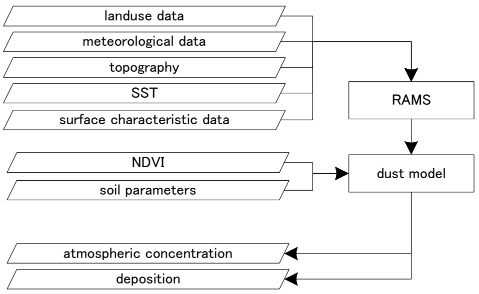

Fig. 1 Model outline

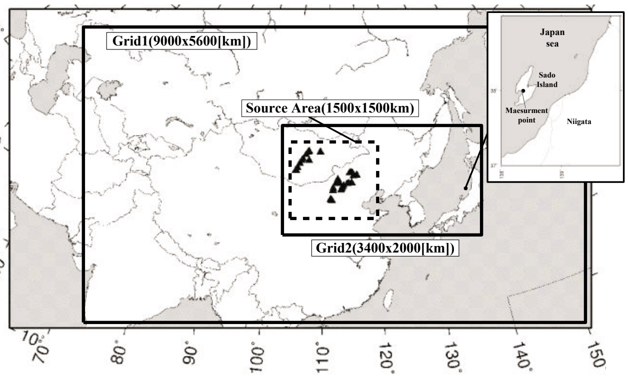

Fig. 2 Calculation area

2. Transport model of ^{137}Cs

In this study, the long-range transport of ^{137}Cs was calculated by equation (1).

$$\frac{\partial C}{\partial t} = -u\frac{\partial C}{\partial x} - v\frac{\partial C}{\partial y} - w\frac{\partial C}{\partial z} + \frac{\partial}{\partial x}\left(K_h\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_h\frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_v\frac{\partial C}{\partial z}\right) + F_{src} - F_{dry} - F_{wet} - \lambda C \tag{1}$$

where, C is ^{137}Cs concentration [Bq/m^3], u, v, and w are wind speed [m/s] of x, y, and z components. K_h, and K_v are horizontal and vertical diffusion coefficients [m^2/s]. These parameters were derived from RAMS. F_{dry}, and F_{wet} are the dry/wet depositions of ^{137}Cs and the λ is the decay constant of ^{137}Cs [1/s]. F_{src} is the ^{137}Cs flux with dust from the earth's surface [Bq/m^2/s].

3. Dust emission model

F_{src}, ^{137}Cs flux from the soil, is calculated by dust emission flux as shown in **Fig.3**. First, the source region can only be grass or farm land, otherwise F_{src} will be 0. Second, the threshold friction velocity u_{*t} is calculated from land use, vegetation and soil condition using equation (2) by Shao (2002).[2]

$$u_{*t} = u_{*t0}(d_s)\cdot f_\lambda \cdot f_w \cdot f_{sc} \cdot f_{cr} \tag{2}$$

where, $u_{*t0}(d_s)$ is threshold friction velocity for particle size d_s. f_λ, f_w, f_{sc}, f_{cr} are functions of surface roughness.

If the friction velocity u_* derived from RAMS, is greater than u_{*t}, dust emission occurred, then F_{src} is calculated by equation (3).

$$\begin{cases} F_{src} = 0 & u_{*t} \le u_* \\ F_{src} = \sum_{i=1}^{I} \breve{F}(d_i)\cdot A_j & u_{*t} > u_* \end{cases} \tag{3}$$

where, A_j, ^{137}Cs contents in the soil by type of land use [kg/Bq], and j is the land use index. The total dust emission rate is derived from summation of salutation flux to Ith for each particle-size bin using Shao (2004).[3] d_i is the particle size of ith group. The emission of dust in the ith group of particle-size at intervals [d_1, d_2] is calculated in equation (4).

$$\breve{F}(d_i) = \int_{d_1}^{d_2} c_y \cdot \eta_{fi} \cdot \left[(1-\gamma) + \gamma\cdot\sigma_p\right]\cdot(1+\sigma_m)\cdot\frac{gQ}{u_*^2}\cdot p_s(d)\cdot \delta d \tag{4}$$

where, g is gravitational acceleration, $p_s(d)$ is particle size distribution,[2] Q is stream wise salutation flux [kg/m/s] derived from Owen's equation (1964)[4], c_y is a dimensionless constant, γ is a function of u_*, and η_{fi} is the total fraction of dust which can be released from a unit of soil mass.[4] σ_p is the free dust to aggregated dust ratio, σ_m is the ratio between the mass of impacting particles and the mass ejected at bombardment.

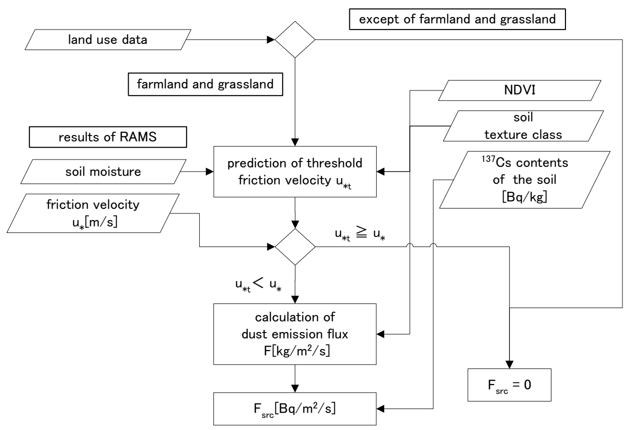

Fig. 3 Calculation of F_{src} from dust emission

4. Source of ^{137}Cs

The ^{137}Cs map of the East Asia continent was produced with observation data from the NIAES. The source area of 1500km x 1500km includes the measurement area of ^{137}Cs centered at 113 degrees longitude and 42 degrees latitude. The ^{137}Cs in the soil was rich in farm land and grass land but ^{137}Cs was not detected in desert areas[5]. For this study, the source was divided into a 30km x 30km mesh. In each mesh, the ^{137}Cs content of the soil was evaluated. When the ^{137}Cs content measurement data exists in the mesh, it is used as source data. Otherwise, the ^{137}Cs content from Table 1 is applied. The map of ^{137}Cs content is shown in **Fig.4**.

Table 1 ^{137}Cs content in the soil[5)]

Type	Averaged ^{137}Cs content[Bq/kg]
grass land 1	52.39
grass land 2	10.85
grass land 3	33.22
Mongolian grass lands	22.56
farm land(Chinese loess)	3.29
farm land(sand)	7.06
desert	ND

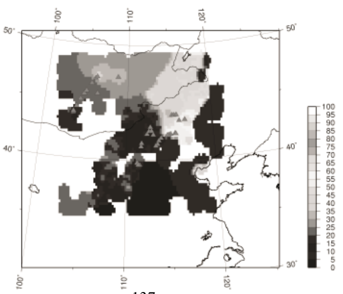

Fig. 4 Map of ^{137}Cs contents [Bq/kg]

IV. Simulation

The simulation for deposition of ^{137}Cs during March, 2006 was carried out when large amounts of ^{137}Cs fallout were measured in Japan. In this simulation, the soil was divided into four particle-size categories: 1-10; 10-20; 20-30 and 30-40 μm. The simulation results were compared with measurements from Sado Island by the NIAES and the monthly deposition data of ^{137}Cs throughout Japan from the Environmental Radiation Database in Japan.[1)] While the results of the simulation show agreement with the measurements of ^{137}Cs deposition, the absolute quantity was underestimated by 0.1-0.5 times. This suggests the uncertainty of the source of ^{137}Cs may cause the difference. The authors compared simulation results with measured results which were normalized by a gross deposition for March equaling to 1.0.

1. Monthly ^{137}Cs deposition in Japan

In March, 2006, the ^{137}Cs deposition was high on the coast of the Sea of Japan at around 200-300 mBq, while on the Pacific Ocean coast area, the deposition was low at around 10 mBq. Results of this simulation indicate good agreement with measured results using a correlation coefficient of 0.77. The model successfully reproduced the tendency of ^{137}Cs deposition in Japan. The comparison simulation and measurements are shown in **Fig. 5**.

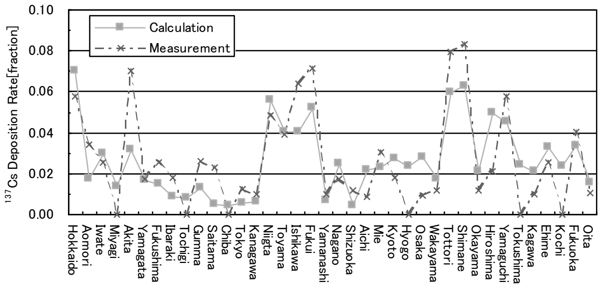

Fig. 5 Normalized ^{137}Cs deposition in Japan(r=0.77)

2. ^{137}Cs deposition on Sado Island

In the case of Sado Island, the amount of ^{137}Cs deposition was measured at 139.6 mBq during March. One peak during March 11th-12th accounts for 70% of the entire deposition during March. The simulation reproduced this peak as seen in **Fig. 6.** According to weather charts, during this period, a low pressure system occurred near inner-Mongolia on the continent around March 9th which then passed through the north of Japan during March 10th-13th. The conditions of dust emissions from the model in **Fig. 7** found that dust emissions occurred when strong winds were covered by low pressure. **Figure 8** shows the distribution of ^{137}Cs deposition during March 11th-12th when the peak of ^{137}Cs deposition occurred on Sado Island suggesting the measured ^{137}Cs was transported from East Asia by this low pressure system which raised the dust levels.

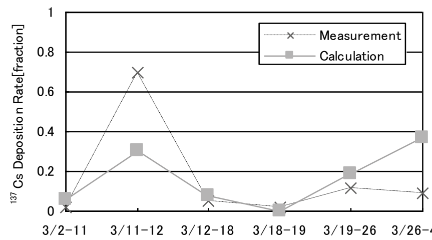

Fig. 6 Normalized ^{137}Cs deposition on Sado Island

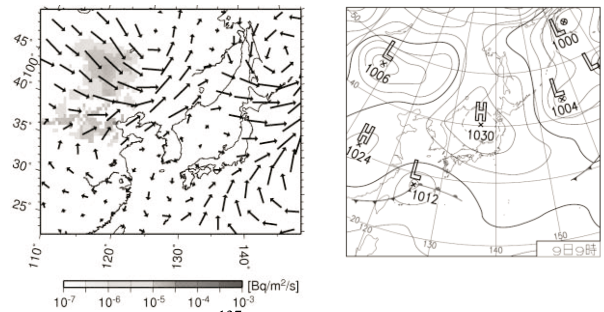

Fig. 7 Distribution of ^{137}Cs with dust emission
left : ^{137}Cs flux on March 9th, 2006 at 6:00,
right : weather chart on March 9th, 2006 at 0:00 by Japan Meteorological Agency

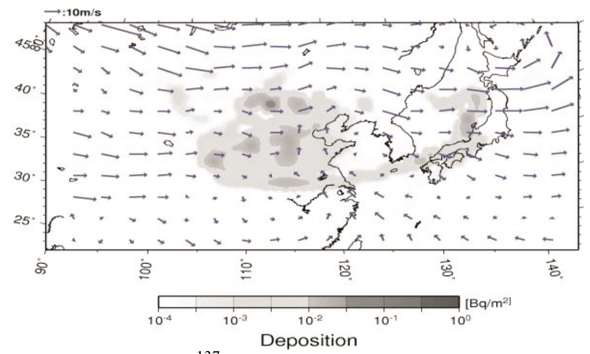

Fig. 8 Distribution of ^{137}Cs deposition (March 11, 2006 at 18:00)

3. The contribution of soil particle-size distribution

The ^{137}Cs deposition for each given particle size category can be seen in **Fig.9**. The averaged deposition of ^{137}Cs in the

1-10, 10-20, 20-30 and 30-40 μm particle size groups were 13.7, 70.0, 6.3 and 10.0 %, respectively. Accordingly, more than 80% of the gross ^{137}Cs deposition has a particle size less than 20 μm.

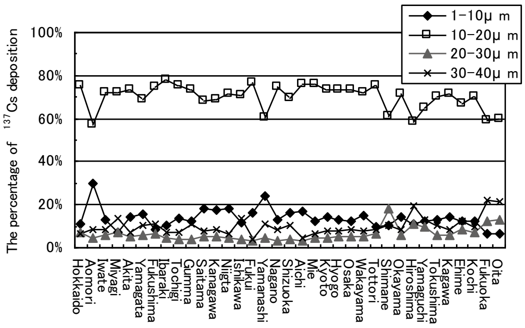

Fig. 9 The ratio of ^{137}Cs deposition by soil particle-size

V. Conclusion

The authors have successfully developed a system, which runs on Microsoft Windows, using long-range transport models of ^{137}Cs with dust entrainment for the yellow sand phenomena. In March of 2006, the simulation results showed congruency with measurements in all parts of Japan with a correlation coefficient of 0.77. The simulation reproduced a peak measurement of ^{137}Cs deposition from Sado Island. However, the simulation showed underestimation in the absolute quantity of ^{137}Cs deposition by 0.1-0.5 times. Likely, this problem is caused by the uncertainty of the source of ^{137}Cs. The simulation results suggest that more than 80% of the gross ^{137}Cs deposition have particle sizes less than 20 μm. Although different radioactivity values can be given to each particle size group for simulation, the actual relationship between radioactivity and soil particle size distribution was unavailable when this simulation was done; therefore, the constant radioactivity values shown in **Tab. 1** were used. Tsukada (2008)[6)], however, suggests that the ^{137}Cs concentration increases as the particle size decreases. Further research of soil particle size will improve calculation conditions and induce less underestimation of actual ^{137}Cs deposition. Simulations applying radioactivity values corresponding to the actual soil particle size distribution will validate this hypothesis. Future plans are to develop a system for predicting radioactive material fallout on varying ground surface conditions after desertification from global warming. This system will distinguish whether the radioactivity fallout fluctuation observed in Japan is caused by nuclear accidents or by natural phenomena.

Acknowledgment

The authors greatly appreciate the fruitful discussion and kind assistance of Professor A. Endo of Ibaraki University.

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