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EVALUATION OF GLOBAL DISTRIBUTION OF FALLOUT Cs-137 BY NUMERICAL SIMULATION WITH COMPARTMENT MODEL

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Abstract

Radionuclides released from the atmospheric nuclear detonation tests started in July 1945 have been globally dispersed and distributed in the atmosphere, the land and the ocean. In this study, the global distribution and accumulation of Cs-137 was evaluated by using the mathematical model for evaluating the dynamic flow and stock of Cs-137 in and between global compartments; in the stratosphere, the troposphere, the surface land, the deep land, the surface ocean, the deep ocean and the bottom ocean (the ocean sediment). The major findings obtained in this study include that global Cs-137 inventory rapidly increases after the end of 1952 and slowly decreases after the peak in Dec. 1962, the peak of the Cs-137 accumulation in the deep land occurs about 5 years and that in the ocean sediment occurs about 17 years after that in the stratosphere; in Dec.1990, total global Cs-137 inventory is estimated about 530 PBq, more than 90% of which is accumulated in the ocean sediment; in the atmosphere, most of Cs-137 is distributed in the high and the middle latitude zone of the Northern Hemisphere; Cs-137 is mainly distributed in the ocean of the Northern Hemisphere; and Cs-137 inventory in the deep land and the ocean sediment much slowly decrease in recent years.

KEYWORDS: *Cs-137, radioactive fallout, global distribution, nuclear detonation test, mathematical model*

1. Introduction

Atmospheric nuclear detonation tests were begun in July 1945 and conducted 423 times in total all over the world until 1980. Their total fission yield is estimated to be about 220 [Mt] (UNSCEAR, 1982). Table 1 shows the brief history of the atmospheric nuclear detonation tests. A portion of the artificial radionuclides released from the atmospheric nuclear detonation tests is transported to the troposphere and the stratosphere with the ascending current caused by the nuclear detonation, and globally dispersed with the general circulation of the atmosphere. Therefore , it takes considerable time for the radionuclides to distribute and accumulate into

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Table 1. Brief summary of atmospheric nuclear detonation test (UNSCEAR,1982).

Year	Nation	No. of Test	Estimated yield (Mt)	
			Fission	Total
1945	USA	3	0.05	0.05
1946	USA	2	0.04	0.04
1948	USA	3	0.1	0.1
1949	USSR	1	0.02	0.02
1951	USA、USSR	17	0.54	0.54
1952	USA、UK	11	6.62	12.62
1953	USA、UK	13	0.29	0.29
1954	USA、USSR	7	30.1	47.6
1955	USA、USSR	17	1.67	3.17
1956	USA、USSR、UK	27	12.3	27.6
1957	USA、USSR、UK	45	10.89	20.89
1958	USA、USSR、UK	83	28.94	60.04
1960	France	3	0.11	0.11
1961	USSR、France	51	25.42	122.32
1962	USSR、USA	77	76.55	217.4
1964	China	1	0.02	0.02
1965	China	1	0.04	0.04
1966	France、China	8	1.3	1.3
1967	France、China	5	1.92	3.22
1968	France、China	6	5.3	7.9
1969	China	1	2.0	3.0
1970	France、China	9	4.55	5.75
1971	France、China	6	1.97	1.97
1972	France、China	5	0.24	0.24
1973	France、China	6	1.65	2.55
1974	France、China	8	1.55	1.7
1976	China	3	2.37	4.12
1977	China	1	0.02	0.02
1978	China	2	0.04	0.04
1980	China	1	0.45	0.6
Total		423	217.2	545.4

each global environmental units: stratosphere, troposphere, land and ocean. In this study, the global distribution and accumulation of Cs-137 was evaluated by using the mathematical model (Shimada *et al.*, 1996) for evaluating the dynamic performance of Cs-137 in global atmospheric environment and its deposition on the land surface mainly from the mass-balanced flow and stock aspects, which was examined with the observed data. Fig. 1 shows some of the results of the comparison between the calculated and observed Cs-137 deposition in different zones.

2. Release to Cs-137 to the global environment

Particles containing Cs-137 except for the Giant Particle released from the nuclear detonation are introduced into the troposphere and the stratosphere at a rate which depends on the scale of the nuclear detonation (Feber, 1965). More Cs-137 may be released to the stratosphere by detonations on a large scale which make high nuclear clouds. In the model we use in this study, the atmosphere and the land are respectively divided into 14 latitude zones; Cs-137 is introduced into the stratosphere and the troposphere in the latitude zone where the nuclear detonation test is conducted. Some large particles containing Cs-137 released to the troposphere locally deposit on the ground immediately after the detonation; we supposed in the model that 99% of Cs-137 introduced into the troposphere may be removed, by considering the mass balance between the total Cs-137 yield and the total global inventory of Cs-137. The case of nuclear test detonations contrasts with that of the Chernobyl accident (April 1986). For the latter situation, all Cs-137 released from the accident are introduced into the troposphere and about 20% of Cs-137 locally deposit (UNSCEAR, 1988). Fig.2(a) and (b) show respectively the estimated Cs-137 [Bq] introduced to the stratosphere and the troposphere. Estimated Cs-137 introduced to the stratosphere is more than 100 times as much as that to the troposphere; most of Cs-137 released from the nuclear detonation tests are introduced to the stratosphere. Released Cs-137 is much high in 1954, 1960 and 1961 - 1962, when huge nuclear detonation tests were conducted.

3. Mathematical Model

3.1 Compartment Model

Global environmental system consists of 7 units in this study as shown in Fig.3. The purpose of this study is to evaluated the distribution and accumulation of Cs-137 in these 7 units; we added the deep land and the ocean sediment compartment to the previous model we had proposed (Shimada *et al.*, 1996), which consists of 54 compartments: stratosphere, troposphere, and land were respectively divided into 14 compartments, surface ocean and deep ocean are respectively divided into six compartments (Fig. 4 and Fig. 5). The deep land and the ocean sediment were respectively divided into 14 latitude zones and 6 blocks. Consequently, the Earth was divided into 74 compartments in this study. In this compartment model, the transfers of Cs-137 from the troposphere up to the stratosphere were basically ignored except for the transfer of Cs-137 into the stratosphere by the ascending air currents caused by the nuclear detonation. Radionuclides are introduced into the troposphere and the stratosphere as described above. The Cs-137 introduced into each compartment in the stratosphere is exchanged laterally between the neighboring compartments in the stratosphere and is transported vertically down to the compartment in the troposphere within the same latitude zone. The Cs-137 introduced into the troposphere is exchanged laterally between the neighboring compartments in the troposphere, and deposited down on the land and ocean compartments of the same latitude zone. The Cs-137 deposited on the land surface is sported to the deep land compartments of the same latitude zone by percolating through the soil with rain. Large scale exchange mechanisms of Cs-137 in the ocean were also incorporated in this model. In this study, the Stommel's ocean circulation model (Stommel, 1958; Pritchard, 1971) was adopted. The radionuclides transported into the marine environment are settled with marine sediment particles. Although the sorption of Cs-137 on the marine particles is weak, the Cs-137 is considered to be fixed in the lattice of certain clay minerals (Duursma and Gross, 1971). In

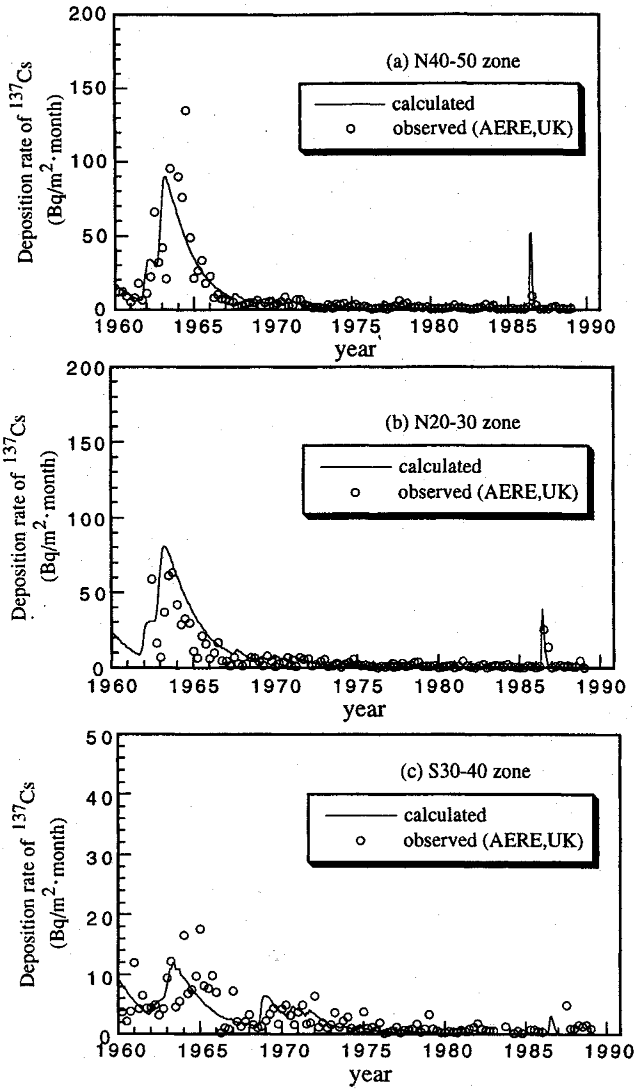

Figure 1. Comparison between the calculated and observed ^{137}Cs deposition in different zones.

this study, we assumed that 15with them (Shimada *et al.*, 1996).

The compartment model is composed of a set of the ordinary differential equations, which describe the mass balance relations of Cs-137 using its inventory in each compartment as the dependent variable. The governing equation for the i-th compartment in the stratosphere can be described as follows:

$$\frac{dM_i}{dt} = \sum_j k_{j,i}M_j - \sum_j k_{i,j}M_i - \lambda_{phys}M_i + I_{ss,i} \quad (i \neq j) \tag{1}$$

Here, M_i [Bq] is the Cs-137 inventory in the i-th compartment; $k_{j,i}$ [$month^{-1}$] is the Cs-

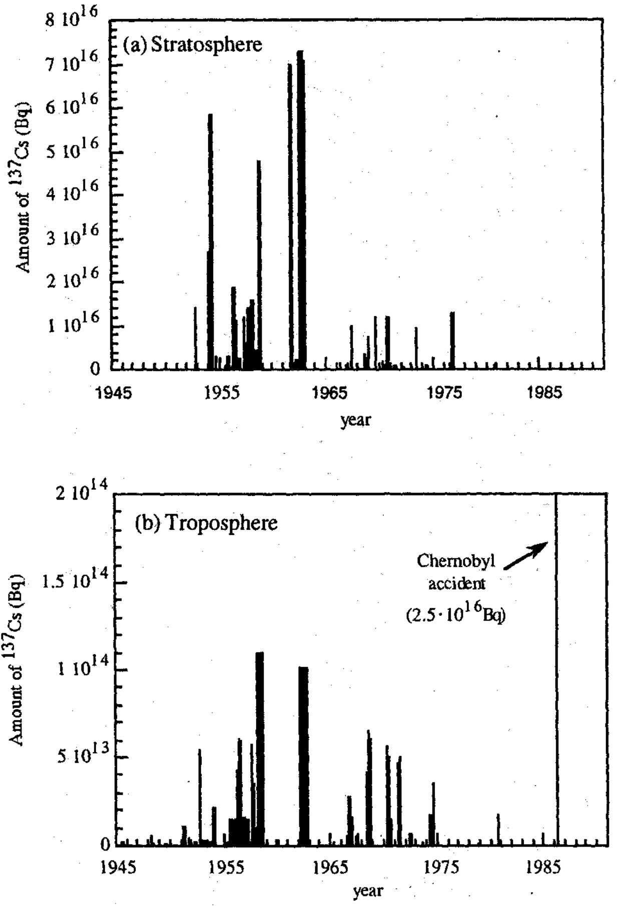

Figure 2. Cs-137 released to the atmosphere

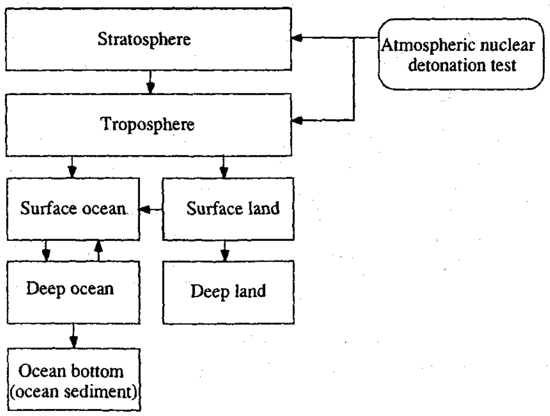

Figure 3. Global environmental system (→ shows the flow of Cs-137.)

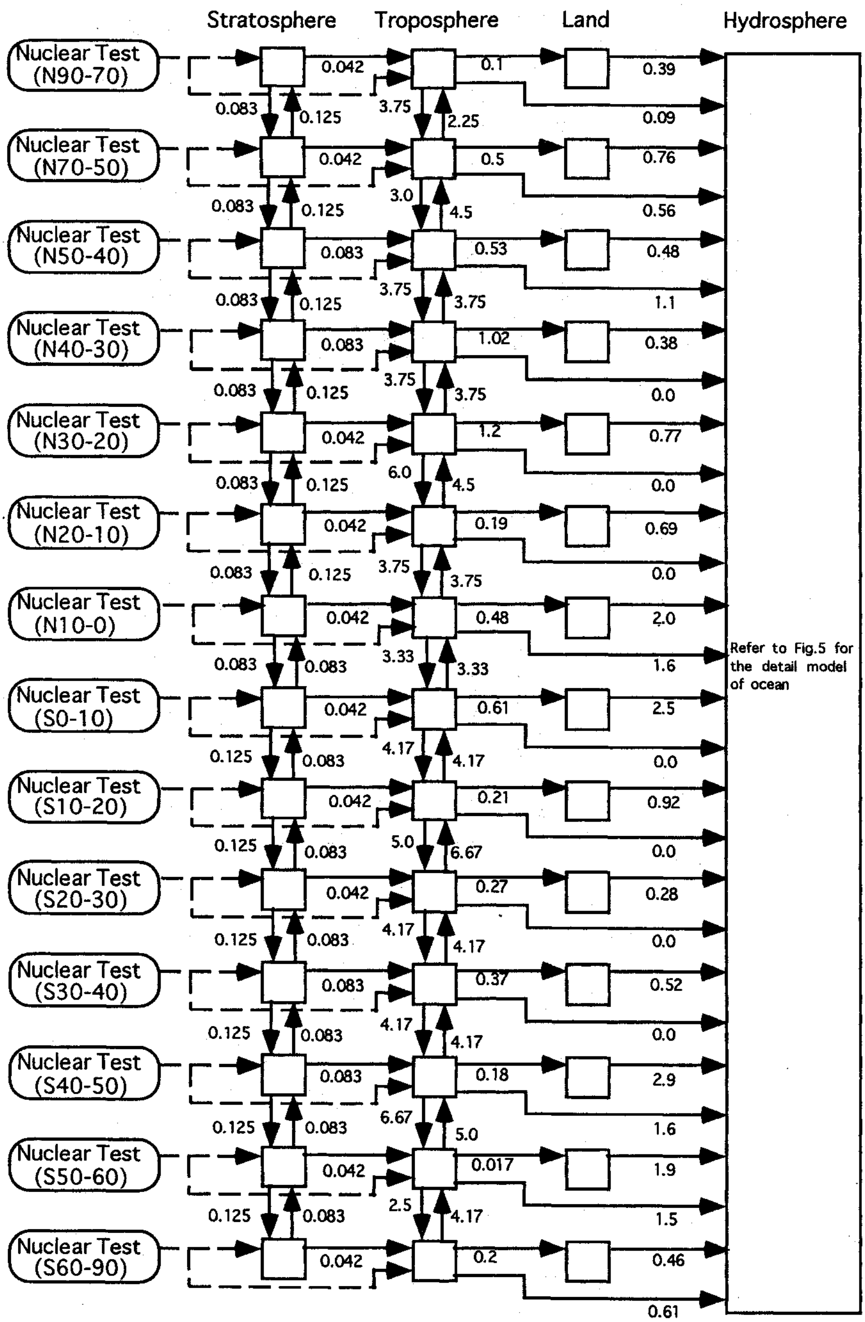

Figure 4. Compartment model for evaluating dynamics performance of the ^{137}Cs in global atmospheric environment and its deposition on land and ocean surfaces (each numerical value beside the arrow is transfer coefficients with the unit of month^{-1}).

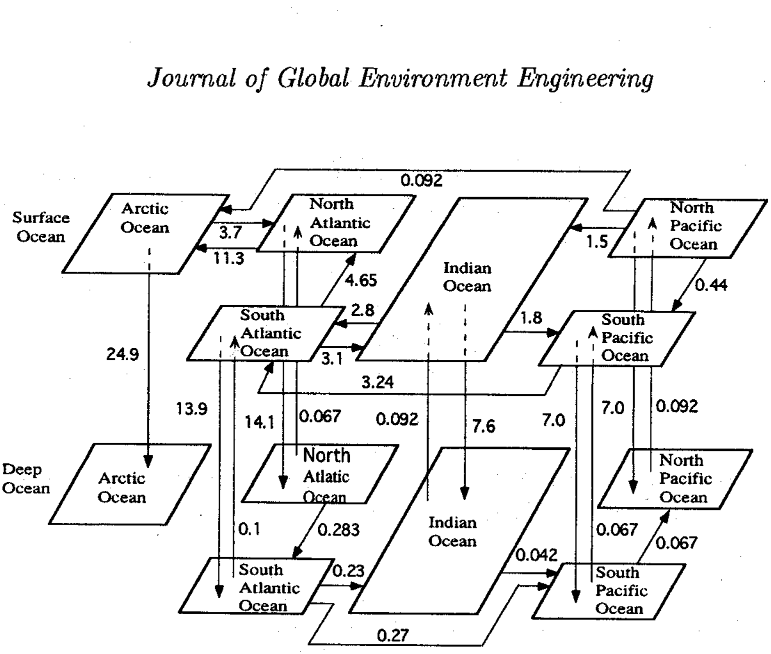

Figure 5. Ocean compartment model used in this research (each numerical value beside the arrow is transfer coefficients with the unit of 10^{-3} month^{-3}).

137 transfer coefficient from the j-th compartment to the neighboring i-th compartment, $k_{i,j}$ $[month^{-1}]$ is that from the i-th to the j-th compartment; λ_{phys} $[month^{-1}]$ is the physical decay constant of Cs-137. $I_{ss,i}$ $[Bq\,month^{-1}]$ is the Cs-137 introduced into the i-th compartment in the stratosphere; which is defined as follows :

$$I_{ss,i} = \begin{cases} M_{nt}Y_{cs}F_{ss,i} & \text{:when nuclear detonation test is conducted} \\ 0 & \text{:when nuclear detonation test is not conducted} \end{cases}$$

As well, the governing equation in the troposphere is as follows:

$$\frac{dM_i}{dt} = \sum_j k_{j,i}M_j - \sum_j (k_{i,j} + d_{i,j})M_i - \lambda_{phys}M_i + I_{ts,i} \quad (i \neq j) \tag{2}$$

Here, $I_{ts,i}$ $[Bq\,month^{-1}]$ is the Cs-137 introduced into the i-th troposphere compartment; which is defined as follows :

$$I_{ts,i} = \begin{cases} M_{nt}Y_{cs}F_{ts,i}P_{res} & \text{:when nuclear detonation test is conducted} \\ 0 & \text{:when nuclear detonation test is not conducted} \end{cases}$$

In Equation(1) and (2), M_{nt} $[Mt]$ is the scale of nuclear detonations, Y_{cs} $[Bq/Mt]$ is the Cs-137 yield for unit scale of nuclear detonations, P_{res} is the fraction of Cs-137 remained in the troposphere soon after locally deposited at the site near the nuclear detonation test, $F_{ss,i}$ is the fraction of Cs-137 released to the i-th stratosphere compartment and $F_{ts,i}$ is that in the troposphere. For the land compartment, it becomes,

$$\frac{dM_i}{dt} = \sum_j d_{j,i}M_j - \sum_j r_{i,j}M_i - (\lambda_{phys} + \lambda_{env})M_i \quad (i \neq j) \tag{3}$$

Here, $d_{j,i}$ $[month^{-1}]$ is the Cs-137 deposition rate coefficient from the j-th troposphere compartment to the i-th land surface compartment in the same latitude zone; $r_{i,j}$ $[month^{-1}]$ is the

Cs-137 runoff rate coefficient from the i-th land surface compartment to the j-th ocean surface compartment containing the same latitude zone. For the deep land compartment,.

$$\frac{dM_i}{dt} = \lambda_{env} M_j - \lambda_{phys} M_i \quad (i \neq j) \tag{4}$$

In Equation(5) and (6), λ_{env} $[month^{-1}]$ is the environmental decay constant of Cs-137 which means the loss of Cs-137 into deeper soil due to percolation with rain. λ_{env} can be described as follows:

$$\lambda_{env} = v/L \tag{5}$$

Here, v $[cm/month]$ is the vertical velocity of Cs-137 percolation and L is the depth of soil in deep land. v is defined (Inoue *et al.*, 1963) as follows:

$$v = v_w/[1 + (\rho_a k_d/\theta)] \tag{6}$$

Here, v_w $[cm/month]$ is the vertical velocity of soil water percolation, θ $[ml/cm^3]$ is the soil water content and k_d $[ml/g]$ is the distribution coefficient of Cs-137 between soil and soil water. ρ_a $[g/cm^3]$ is the bulk soil density. Assuming that Cs-137 should uniformly percolate through soil, v_w can be described as follows:

$$v_w = \beta(1-e)R/\theta \tag{7}$$

Here, R $[cm/month]$ is the average precipitation, e [-] is the rate of evaporation, β [-] is the fraction of the effective precipitaion($(1-e)R$) percolated through soil. e is set to 0.5 in this study. For the surface ocean compartment,

$$\frac{dM_i}{dt} = \sum_j (d_{j,i} + w_{j,i}) M_j - \sum_j (w_{i,j} + s_{i,j}) M_i - \lambda_{phys} M_i \quad (i \neq j) \tag{8}$$

and for the deep ocean compartment,

$$\frac{dM_i}{dt} = \sum_j (w_{j,i} + s_{j,i}) M_j - \sum_j (w_{i,j} + s_{i,j}) M_i - \lambda_{phys} M_i \quad (i \neq j) \tag{9}$$

Here, $d_{j,i}$ $[month^{-1}]$ is the Cs-137 deposition rate coefficient from the j-th troposphere compartment to the i-th surface ocean compartment containing the same latitude zone; $w_{j,i}$ $[month^{-1}]$ is the Cs-137 transfer coefficient from the j-th compartment to the i-th compartment of the surface and deep ocean; $s_{i,j}$ $[month^{-1}]$ is the Cs-137 sedimentation rate coefficient from the i-th surface ocean compartment down to the j-th deep ocean compartment. For the ocean sediment compartment,

$$\frac{dM_i}{dt} = s_{j,sink} M_j - \lambda_{phys} M_i \quad (i \neq j) \tag{10}$$

Here, $s_{i,sink}$ is the Cs-137 sedimentation rate coefficient from the i-th compartment of the deep ocean to the ocean bottom (sediment).

3.2 Numerical simulation

The set of ordinary differential equations were solved numerically by the Runge-Kutta-Gill Method (Romanelli, 1967). The release of Cs-137 to the environment were determined based on the nuclear detonation test records (date, place and scale) (Ichikawa, 1984; UNSCEAR, 1982;

Table 2. Parameter values of sedimentation rate coefficients $[month^{-1}]$

Ocean block	$S_{i,j}$, $S_{j,sink}$ Value used in this study	Reported[a]
Arctic Ocean	0.166	0.083~0.332
North Pacific Ocean	0.051	0.025~0.102
South Pacific Ocean	0.051	0.025~0.102
Indian Ocean	0.051	0.025~0.101
North Pacific Ocean	0.047	0.023~0.093
South Pacific Ocean	0.047	0.023~0.093

a) Values derivedform Nagaya, 1984.

Japan Atomic Power Industry Conference, 1985; Matthews, 1989). Since 1980 nuclear detonation tests in the atmosphere have been stopped. However, the Chernobyl accident occurred on 26 April, 1986 caused a temporal release of radionuclides into the troposphere (OECD, 1987), which was also included in this model calculation. As the initial condition (before July 1945), the Cs-137 inventory in each compartments was set to zero. And the numerical simulation was executed every one month from 1945 to 1990. The value of the parameters needed for the simulation are shown in Fig.3 (Baumgartner and Reichel, 1975; Dobson, 1956; Eisenbud, 1973; Kida, 1977; List and Telegadas, 1969; Newell, 1963; Newell, 1971; Pannetier, 1970) and Fig.4 (Duursma and Gross, 1971; Stommel, 1958) for the transfer and deposition rate coefficients, in Table 2 for the sedimentation rate coefficients and in Table 3 for the environmental decay constant; λ_{env}. M_{nt} was determined based on the nuclear detonation test records and given once every month in the period 1945 through 1990. Y_{cs} was set to 5.9 $[PBq/Mt]$ (watabe, 1984). $F_{ss,i}$ and $F_{ts,i}$ are dependent on the location and scale of the nuclear detonation; based on the relationship amonth the nuclear detonation scale (Feber, 1965), the fractional values of these two parameters were determined for each land compartment at the site of the nuclear detonation test.

4. Results and discussion

4.1 Total mass balance of Cs-137

Total Cs-137 inventory in the global environment and in the 7 environmental units were calculated respectively. Fig.5(a)$\sim$ (h) show the results. Total Cs-137 inventory radically increases since the end of 1952, and slowly decreases after the peak in Dec. 1962. In Dec. 1990, total Cs-137 inventory is estimated about 530 PBq, about 91% of which is accumulated in the ocean sediment. Table 4 shows the relative inventory of Cs-137 in the global environment in five years increments. Cs-137 distributed to the ocean sediment is increasing. Cs-137 inventory in the deep land is much less than that in other units; Cs-137 accumulated in the deep land is relatively near zero. Cs-137 inventory in each environmental unit has its peak time; the peak time of the Cs-137 accumulation occurs fastest in the stratosphere, which is followed by the troposphere, the land surface, the surface ocean, the deep ocean, the deep land and the ocean sediment in this order. The peak of the Cs-137 accumulation in the deep land occurs about 5

Table 3. Parameter value of Cs-137 percolation through soil.

Parameter		Value used in this study	Reported
k_d	[ml/g]	6000	200 ~ 17000[a]
ρ_a	[g/cm^3]	1.3	0.7 ~ 1.8[b),c)]
θ	[ml/cm^3]	0.5	0.2 ~ 0.8[c]
e	[-]	0.5	0.2~ 0.9[c]
β	[-]	0.7	0.6 ~ 0.9[d]

a) Values derived from Radioactive Waste Management Center, 1990.
b) Values derived from Noguchi and Kawad, 1987.
c) Values derived from Kyuma et al., 1993.
d) Values derived from Edetorial Committee for the Handbook of Meteorology, 1959; Kawabata, 1961.

Table 4. Relative inventory of Cs-137 in the Global environment

	Jan.1965	Jan.1970	Jan.1975	Jan.1980	Jan.1985	Jan .1990
Stratosphere	15	3	1	0	0	0
Troposphere	1	0	0	0	0	0
Land surface	1	0	0	0	0	0
Deep land	0	0	0	0	0	0
Surface ocean	43	25	12	6	3	3
Deep ocean	22	29	22	14	8	6
Ocean sediment	18	43	65	80	89	91
Total (%)	100	100	100	100	100	100
(PBq)	836	781	721	655	585	544

years late and that in the ocean sediment occurs about 17 years after that in the stratosphere. Cs-137 inventory in the deep land and the ocean sediment decrease much slowly after the peak, which means that Cs-137 can remain long in the land and the ocean in the future.

4.2 Cs-137 distribution in the atmosphere

Table 5 shows the relative inventory of Cs-137 in the stratosphere and the troposphere in five years increments. In the stratosphere, about 90% of Cs-137 is distributed in the Northern Hemisphere, mainly within the high latitude zone after 1965's. In the troposphere, most of Cs-137 is distributed mainly within the N90-70 and N70-50 zones after 1960's. These results shows that the distribution of Cs-137 in the atmosphere depends largely on its release from the huge nuclear tests conducted between 1954 and 1962 mainly in the Northern Hemisphere (Ichikawa, 1984; Japan Atomic Power Industry Conference, 1985; Matthews, 1989;UNSCEAR, 1982).

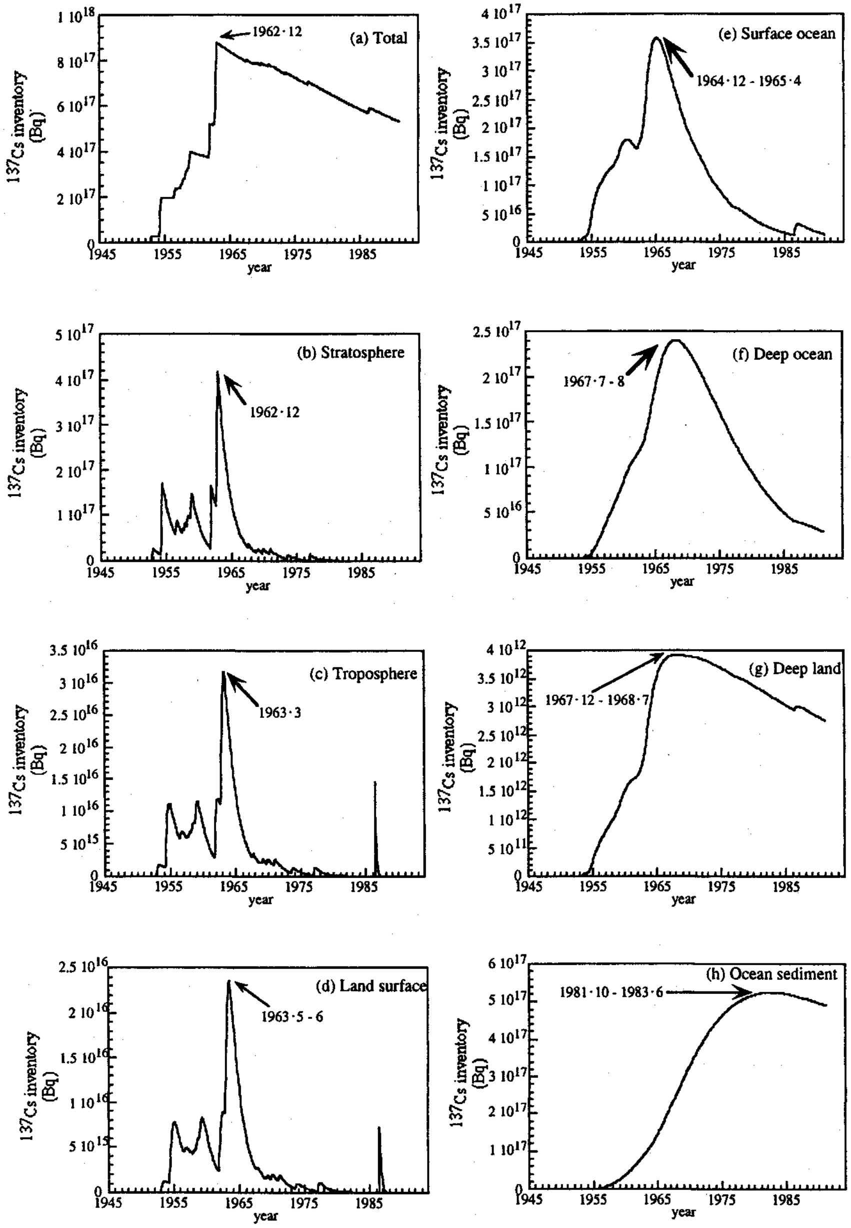

Figure 6. Cs-137 inventory in the global environment

Table 5. Relative inventory of Cs-137 in the atmosphere

	Jan.1965		Jan.1970		Jan.1975		Jan.1980		Jan.1985		Jan.1990	
	SS	TS	SS	TS	SS	TS	SS	TS	SS	TS	SS	TS
N90-70	48	21	22	14	30	15	40	18	41	18	40	17
N70-50	28	26	23	21	23	20	25	24	25	23	24	22
N50-40	12	14	26	13	15	12	13	13	12	13	12	12
N40-30	6	9	10	9	9	9	7	9	6	9	6	9
N30-20	3	6	4	6	6	6	6	6	5	6	5	6
N20-10	2	6	2	7	3	7	4	7	3	7	3	7
N10-0	1	4	1	5	1	5	2	5	2	5	2	5
S0-10	0	3	1	5	1	5	1	4	1	4	1	4
S10-20	0	3	2	5	2	5	1	4	1	4	1	4
S20-30	0	2	3	3	4	4	0	2	1	3	1	3
S30-40	0	2	2	3	2	3	0	2	1	3	1	3
S40-50	0	1	2	3	1	3	0	2	0	2	1	3
S50-60	0	2	1	4	1	4	0	2	1	3	1	3
S60-90	0	1	1	2	2	2	1	2	1	2	2	2
Total (%)	100	100	100	100	100	100	100	100	100	100	100	100
(PBq)	121	12.2	21.1	2.53	5.54	0.63	1.68	0.17	0.13	0.13	0.0057	0.0006

(SS: Stratosphere, TS: Troposphere)

4.3 Cs-137 distribution in the land

Table 6 shows the relative inventory of Cs-137 in the surface and deep land in five years increments. More than 80% of Cs-137 is distributed in the land of the Northern Hemisphere. In the surface land, Cs-137 is distributed most within N40-30 which is followed by N70-50, N50-40 and N30-20. In the deep land, the distribution of Cs-137 is almost the same as in the surface. In the equatorial zone, the distribution of Cs-137 in the deep land is about 6 times as much as that in the surface land, which may be caused by the percolation through the soil (refer to *Equations*(7) ~ (9))with the heavy precipitation in this zone.

4.4 Cs-137 distribution in the ocean

Table 7 shows the relative inventory of Cs-137 in the surface ocean, the deep ocean and the ocean sediment in five years increments. In these three units of the ocean, Cs-137 is distributed most in the North Pacific Ocean which is followed by the North Atlantic Ocean, the Indian Ocean, the South Pacific Ocean, the South Atlantic Ocean and the Arctic Ocean in this order. Most of Cs-137 is distributed in the Northern Hemisphere ocean, which is the same as in the atmosphere and the land. In the surface ocean, where the most of marine products are supplied, about 54% of Cs-137 is distributed in the North Pacific Ocean, 19% in the North Atlantic and 15% in the Indian Ocean in Jan. 1990.

Table 6. Relative inventory of Cs-137 in the land

	Jan.1965		Jan.1970		Jan.1975		Jan.1980		Jan.1985		Jan.1990	
	SL	DL	SL	DL	SL	DL	SL	DL	SL	DL	SL	DL
N90-70	7	4	4	4	5	4	6	4	6	4	6	4
N70-50	21	24	18	24	17	24	19	24	19	24	19	25
N50-40	19	14	19	14	18	14	18	14	18	14	18	14
N40-30	32	19	31	19	32	19	33	19	32	19	31	19
N30-20	11	17	13	17	12	17	12	17	12	17	12	16
N20-10	2	3	2	3	3	3	2	3	2	3	2	3
N10-0	1	6	2	6	2	6	2	6	2	6	1	6
S0-10	1	6	1	6	1	6	1	6	1	6	1	6
S10-20	1	2	1	2	1	2	1	2	1	2	1	2
S20-30	3	1	5	1	5	1	3	1	4	1	5	1
S30-40	1	2	3	2	3	2	2	2	2	2	3	2
S40-50	0	1	0	1	0	1	0	1	0	1	0	1
S50-60	0	0	0	0	0	0	0	0	0	0	0	0
S60-90	1	1	1	1	1	1	1	1	1	1	1	1
Total (%)	100	100	100	100	100	100	100	100	100	100	100	100
(PBq)	10.7	0.0036	1.99	0.0039	0.53	0.0037	0.15	0.0034	0.011	0.003	0.0005	0.0028

(SL: Surface land, DL: Deep land)

Table 7. Relative inventory of Cs-137 in the ocean

	Jan.1965			Jan.1970			Jan.1975			Jan.1980			Jan.1985			Jan.1990		
Ocean	SO	DO	SD	SO	DO	SD	SO	DO	SD	SO	DO	SD	SO	DO	SD	SO	DO	SD
Arctic	3	4	9	1	2	9	1	1	7	1	0	6	1	0	6	1	1	6
North Atlantic	24	29	26	19	29	28	16	25	28	15	23	27	12	21	27	19	23	26
South Atlantic	3	5	6	4	4	5	5	5	5	5	5	5	6	6	5	4	5	5
Indian	14	15	19	15	14	16	18	15	16	19	16	16	20	16	16	15	15	16
North Pacific	51	40	33	52	45	36	51	47	38	51	48	40	51	49	40	54	49	41
South Pacific	5	7	7	7	6	6	9	7	6	9	8	6	10	8	6	7	7	6
Total (%)	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
(PBq)	357	187	147	192	230	333	89	161	464	41	94	518	16	49	520	17	32	496

(SO: Surface Ocean, DO: Deep Ocean, SD: Sediment)

5. Conclusion

The major findings obtained in this study are summarized as follows:

1. Global Cs-137 inventory rapidly increases after the end of 1952 and slowly decreases after the peak in Dec. 1962.
2. The peak accumulation of Cs-137 in the deep land occurs about 5 years late and that in the ocean sediment occurs about 17 years late after that in the stratosphere.
3. In Dec. 1990, total Cs-137 inventory is estimated about 530 PBq, more than 90% of which is distributed in the ocean sediment.
4. In the atmosphere and the land, more than 80% of Cs-137 is distributed in the Northern Hemisphere, especially in the high and middle latitude zones. In the ocean, Cs is mainly distributed in the North Pacific Ocean, the North Atlantic Ocean and the Indian Ocean.
5. Cs-137 inventory in the deep land and the ocean sediment much slowly decreases in recent years; Cs-137 can remain long in the future.

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Nomenclature

$d_{i,j}$: the ^{137}Cs deposition rate coefficient from the i-th troposphere compartment to the j-th land surface compartment in the same latitude zone (month^{-1})

e : the rate of evaporation (-)

$F_{ss,i}$: the fraction of ^{137}Cs released to the i-th stratosphere compartment (-)

$F_{ts,i}$: the fraction of ^{137}Cs released to the i-th troposphere compartment (-) ($F_{ss,i} + F_{ts,i} = 1$)

$I_{ss,i}$: the ^{137}Cs introduced into the i-th compartment in the stratosphere (Bq month^{-1})

$I_{ts,i}$: the ^{137}Cs introduced into the i-th compartment in the troposphere (Bq month^{-1})

k_d : the distribution coefficient of ^{137}Cs between soil and soil water (ml/g)

$k_{i,j}$: the ^{137}Cs transfer coefficient from the i-th to the j-th compartment in and between the stratosphere and the troposphere (month^{-1})

L : the depth of soil (cm)

M_i : the ^{137}Cs inventory in the i-th compartment (Bq)

M_{nt} : the scale of nuclear detonation (Mt)

P_{res} : the fraction of ^{137}Cs remained in the troposphere soon after locally deposited at the site near the nuclear detonation test (-)

R : the average precipitation (cm/month)

$r_{i,j}$: the ^{137}Cs runoff rate coefficient from the i-th land surface compartment to the j-th ocean surface compartment containing the same latitude zone (month^{-1})

$s_{i,j}$: the ^{137}Cs sedimentation rate coefficient from the i-th surface ocean compartment down to the j-th deep ocean compartment (month^{-1})

$s_{i,sink}$: the ^{137}Cs sedimentation rate coefficient from the i-th compartment of the deep ocean to the ocean bottom (sediment) (month^{-1})

v : the vertical velocity of ^{137}Cs percolation (cm/month)

v_w : the vertical velocity of soil water percolation (cm/month)

$w_{i,j}$: the ^{137}Cs transfer coefficient from the i-th compartment to the j-th compartment of the surface and deep ocean (month^{-1})

Y_{cs} : the ^{137}Cs yield for unit scale of nuclear detonations (Bq/Mt)

β : the fraction of the precipitation effective for percolating through soil (-)

θ : the soil water content (ml/cm^3)

ρ_a : the bulk soil density (g/cm^3)

λ_{env} : the environmental decay constant of ^{137}Cs (month^{-1})

λ_{phys} : the physical decay constant of ^{137}Cs (month^{-1})